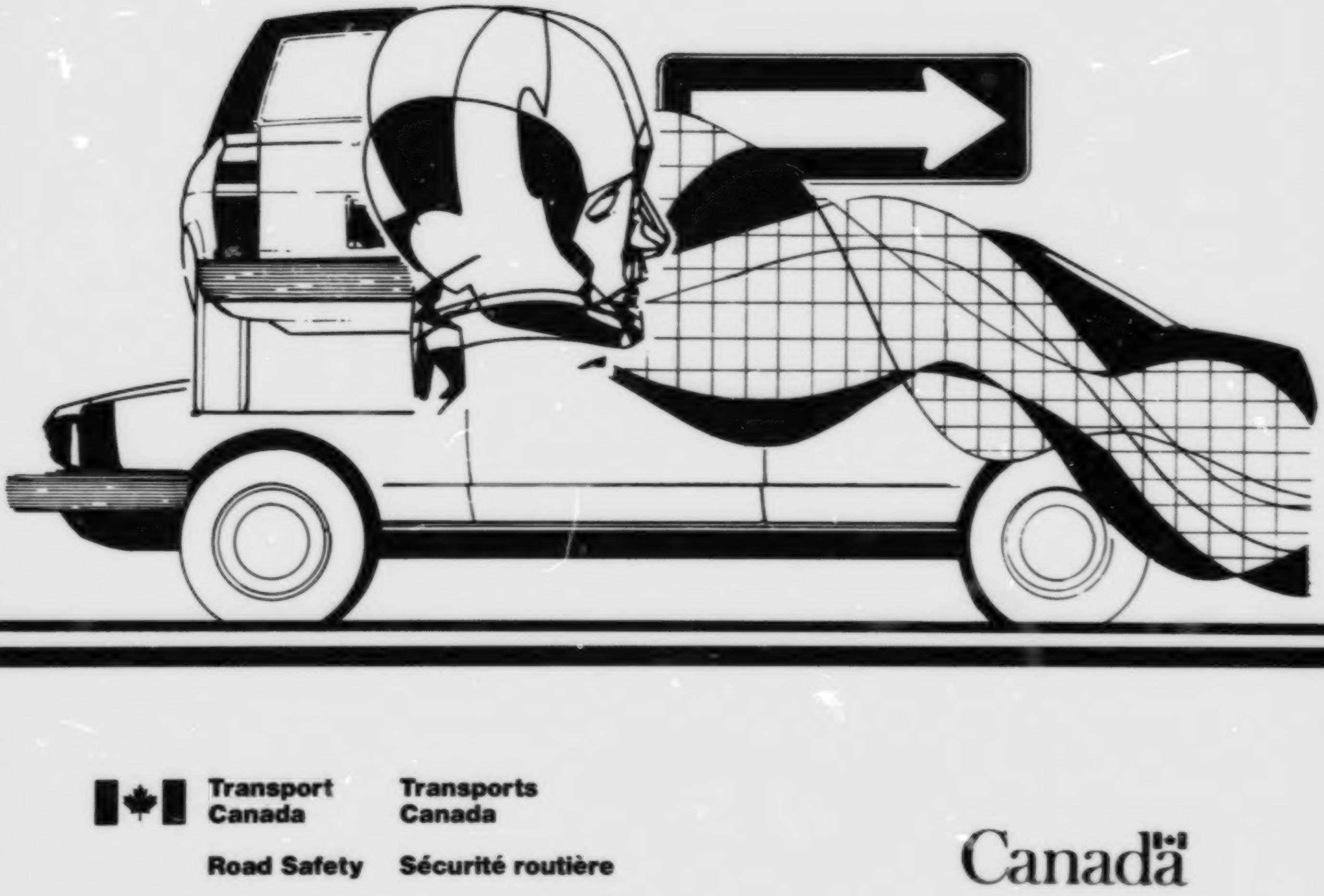
TP 10727(E)

ATTENTION AND PERFORMANCE WHILE DRIVING WITH AUXILIARY IN-VEHICLE DISPLAYS



Transport Canada | Transports Canada

Road Safety | Sécurité routière

Canada

ATTENTION AND PERFORMANCE WHILE DRIVING WITH AUXILIARY IN-VEHICLE DISPLAYS

Y. Ian Noy
Ergonomics Division
Traffic Safety Standards and Research
Transport Canada

February 1990

91-02927/

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 10727 (E)

2. Project No.

3. Recipient's Catalogue No.

4. Title and Subtitle
Attention and Performance While Driving With Auxiliary In-vehicle Displays

5. Publication Date
December 1990

6. Performing Organization Document No.

7. Author(s)
Ian Noy

8. Transport Canada File No.
ASF 3261-228

9. Performing Organization Name and Address
Road Safety and Motor Vehicle Regulation
Transport Canada
Ottawa, K1A 0N5

10. DSS File No.

11. DSS or Transport Canada Contract No.

12. Sponsoring Agency Name and Address
Road Safety and Motor Vehicle Regulation
Transport Canada
Ottawa, K1A 0N5

13. Type of Publication and Period Covered
Final

14. Sponsoring Agency Code

15. Supplementary Notes

16. Project Officer
Ian Noy

17. Abstract

Emerging intelligent vehicle-highway systems technology will have a profound impact on the design of future driver interfaces. A major element of this technology is the development of advanced driver information systems. A series of three experiments were conducted to investigate basic human factors issues relating to the design and use of auxiliary in-vehicle displays. A total of thirty healthy male and female students with a minimum of three year's driving experience participated in these studies. Subjects drove in a moving-base driving simulator and performed auxiliary cognitive tasks on a CRT display located on the right side instrument panel. Subjects were instructed to perform both the auxiliary task and the driving task to the best of their abilities but to give priority to the driving. Eleven dependent variables provided measures of driving performance, attentional behaviour, auxiliary task performance and workload. In addition, on-line eye movement recordings indicated whether the subject looked at the roadway or at the computer display. In the first experiment, a spatial perception task was used to investigate the effects of auxiliary task difficulty and driving difficulty on drivers' attention and performance under time-shared conditions. The results indicated that performing auxiliary tasks while driving can significantly degrade performance. The effects were manifested even more strongly in subjects' attentional responses. The second experiment examined the role of auxiliary task resource structure. This group of subjects performed a verbal memory task which required less sharing of resources with the driving task than the perception task. The results failed to support Multiple Resource Theory predictions of reduced intrusion, indicating that the nature and extent of intrusion were relatively robust with respect to task resource structure. The third experiment examined the effects of task utility. Subjects received monetary rewards depending upon their performance on the memory task. The results provided no evidence that the payment of bonuses was effective in shifting relative resource allocation between these tasks. The results of these experiments clarify theoretical considerations for the development of ergonomic design guidelines for automotive displays. The methodology developed for these studies is well suited for further studies into drivers' visual attention and performance under a variety of concurrent multitask conditions.

18. Key Words Human Factors, attention, performance, driving task, driver interface, auxiliary displays, road safety

19. Distribution Statement
Limited number of copies available from Sponsoring agency on request

20. Security Classification (of this publication)
Unclassified

21. Security Classification (of this page)

22. Declassification (date)

23. No. of pages
130

24. Price
N/A.

02-0149 (09-88)

ABSTRACT

Emerging intelligent vehicle-highway systems technology will have a profound impact on the design of future driver interfaces. A major element of this technology is the development of advanced driver information systems. A series of three experiments were conducted to investigate basic human factors issues relating to the design and use of auxiliary in-vehicle displays. A total of thirty healthy male and female students with a minimum of three year's driving experience participated in these studies. Subjects drove in a moving-base driving simulator and performed auxiliary cognitive tasks on a CRT display located on the right side instrument panel. Subjects were instructed to perform both the auxiliary task and the driving task to the best of their abilities but to give priority to the driving. Eleven dependent variables provided measures of driving performance, attentional behaviour, auxiliary task performance and workload. In addition, on-line eye movement recordings indicated whether the subject looked at the roadway or at the computer display. In the first experiment, a spatial perception task was used to investigate the effects of auxiliary task difficulty and driving difficulty on drivers' attention and performance under time-shared conditions. The results indicated that performing auxiliary tasks while driving can significantly degrade performance. The effects were manifested even more strongly in subjects' attentional responses. The second experiment examined the role of auxiliary task resource structure. This group of subjects performed a verbal memory task which required less sharing of resources with the driving task than the perception task. The results failed to support Multiple Resource Theory predictions of reduced intrusion, indicating that the nature and extent of intrusion were relatively robust with respect to task resource structure. The third experiment examined the effects of task utility. Subjects received monetary rewards depending upon their performance on the memory task. The results provided no evidence that the payment of bonuses was effective in shifting relative resource allocation between these tasks. The results of these experiments clarify theoretical considerations for the development of ergonomic design guidelines for automotive displays. The methodology developed for these studies is well suited for further studies into drivers' visual attention and performance under a variety of concurrent multitask conditions.

TABLE OF CONTENTS

TABLE OF CONTENTS ii
LIST OF FIGURES v
LIST OF TABLES vi
EXECUTIVE SUMMARY vii
INTRODUCTION 1
  Purpose of the Study 1
  Developments in Driver Interface Design 2
  The Role of Human Factors 4
  Human Factors Issues 5
  Driver Inattention 7
  The Effects of Auxiliary Tasks on Driving 10
RESEARCH DESIGN 14
  Problem Definition 14
  Research Objectives 16
  Research Overview 17
EXPERIMENT ONE 18
  Purpose 18
  Methodology 18
    Experimental Design 18
    Experimental Set-Up 19
    Apparatus 22
      UTIAS Flight Simulator 22
      Attention Monitoring System 25
    Experimental Tasks 25
      Driving Task 25
      Spatial Perception Task 27
    Dependent Measures 28
      Driving performance 28
      Attentional Behaviour 30
      Auxiliary Task Performance 30
      Workload 31
    Test Trial 31
    Roads Library 32
    Subjects 34
    Procedures 35
      Subject Processing and Training 35
      Testing 36
  Results 37
    Statistical Analyses 38

        Effect of Task Load on Driving 37
        Effect of Driving Load on Driving Performance..........................41
        Effects of Task Load on Attention 42
        Effects of Driving Load on Attention 43
        Effects of Driving and Task Load on Task Performance...................47
        Effects of Gaze Direction on Driving...................................48
        Effects of Task Load on Mental Workload................................52
        Serial versus Parallel Effects 54
        Effects of Field Dependence 58
    Discussion..**61**
      Methodology Evaluation...61
      Mutual Intrusion and Inferences 62
      Evidence for Driver Adaptation 63
EXPERIMENT TWO **65**
    Purpose **65**
    Methodology **67**
      Experimental Design..67
      Experimental Protocol 68
      Memory Task 69
      Dependent Measures 71
      subjects...71
      Procedures...72
    Results...**73**
      Driving Performance..74
      Attention..76
      Auxiliary Task Performance 79
      Serial versus Parallel Effects..81
      Field Dependence 85
      Gaze Direction...86
      Mental Workload 86
    Discussion..**87**
      Task Resource Structure..87
      Generalized Response Cycle..89
      Mechanisms of Attention 91
EXPERIMENT THREE..**95**
    Purpose **95**
    Methodology **96**
      Experimental Design..96
      Experimental Protocol 97
      Bonus Condition..97
      Subjects 98

Results 98
Driving Performance 98
Attention 100
Auxiliary Task Performance 100
Discussion 102
DISCUSSION AND CONCLUSIONS 103
REFERENCES 109
APPENDIX A - Data Tables 121

LIST OF FIGURES

Figure 1: Attention and Performance in Driving 9
Figure 2: Conceptual Framework 15
Figure 3: Experimental Set-Up 21
Figure 4: UTIAS Flight Research Simulator 22
Figure 5: Driver Workstation 23
Figure 6: Dual Task Decrements in Driving Performance 39
Figure 7: Headway as a Function of Task Load 41
Figure 8: TLC as a Function of Road Curvature 42
Figure 9: Dwell Time as a Function of Task Load 44
Figure 10: Dwell Time as a Function of Road Curvature 45
Figure 11: Look Frequency as a Function of Road Curvature 45
Figure 12: Viewing Ratio as a Function of Road Curvature 47
Figure 13: Reaction Time as a Function of Auxiliary Task Difficulty 49
Figure 14: Std. Dev. Lane Position as a Function of Road Curvature 56
Figure 15: TLC as a Function of Road Curvature 57
Figure 16: Viewing ratio Versus TLC 64
Figure 17: Auxiliary Task Normative Data 71
Figure 18: Baseline Condition 76
Figure 19: Curvature-Task Interactive Effects on Look Frequency 78
Figure 20: Dwell Time 79
Figure 21: Task-Difficulty Interactive Effects on Auxiliary Task Performance 81
Figure 22: TLC as a Function of Auxiliary Task Condition 84
Figure 23: Std. Dev. Lane Position as a Function of Auxiliary Task Condition 84
Figure 24: Viewing Ratio as a Function of Auxiliary Task Condition 85
Figure 25: Response Cycle 90

LIST OF TABLES

Table 1: Table of Dependent Variables 28
Table 2: Summary of 5 X 4 ANOVA 38
Table 3: Effect of Auxiliary Task on Driving 38
Table 4: Summary of 4 X 4 ANOVA of Driving Variables 40
Table 5: Summary of 4 X 4 ANOVA of Attention Variables 43
Table 6: Summary of 4 X 4 ANOVA of Auxiliary Task Performance 48
Table 7: Paired T-Test Results for 'Inside' and 'Outside' Looking Conditions 50
Table 8: Mean Stop Reaction Time 52
Table 9: Mean Increase in Workload Ratings Over Baseline 53
Table 10: Summary of 2-way ANOVA Comparing Parallel and Serial Effects 55
Table 11: Field (In)dependent Group Membership 59
Table 12: Summary of 3-way ANOVA Testing Effects of Field Dependence 60
Table 13: Summary of 2 X 5 X 4 and 2 X 4 X 4 ANOVA's 75
Table 14: Summary of 2 X 4 X 4 ANOVA of Attention Variables 77
Table 15: Summary of 4 X 4 ANOVA of Auxiliary Task Performance 80
Table 16: Summary of 2 X 5 X 4 ANOVA's 82
Table 17: Paired T-Test Results for 'Inside' and 'Outside' Looking Conditions 86
Table 18: Summary of ANOVA of Workload Scales 87
Table 19: Summary of 2 X 4 X 4 ANOVA 99
Table 20: Summary of 2 X 4 X 4 ANOVA of Attention Variables 101
Table 21: Summary of 2 X 4 X 4 ANOVA of Transformed Correct Reaction Time (NEGRT) 101

1. EXECUTIVE SUMMARY

Emerging intelligent vehicle-highway system technologies will have a profound impact on the design of future driver interfaces. A major element of this technology is the development of advanced driver information systems. However, few studies have examined how auxiliary automobile displays affect drivers' performance and attentional response. A series of three experiments was conducted to investigate basic human factors issues relating to the design and use of auxiliary in-vehicle displays. A standard dual task paradigm was used in which three groups of subjects drove in a moving-base driving simulator and performed auxiliary cognitive tasks on a CRT display located on the right side instrument panel.

The rear section of the Flight Research Simulator at the University of Toronto was configured to represent a conventional compact-size vehicle. The driver's forward view of the roadway was projected by an IRIS 3020 colour graphics system through a collimating optical system onto a 40 degrees by 30 degrees display. A specially-built Attention Monitoring System, comprising an eye tracker (using electro-oculography) and a head tracker (using infra-red transducers), was used to monitor subjects' eye movements to determine whether the subject looked at the roadway or at the auxiliary display.

The driving task required subjects to maintain constant lane position and headway as they drove at about 60 KPH over a winding roadway. Upon reaching a predetermined distance, the lead vehicle began to decelerate rapidly and subjects were required to react by depressing the brake pedal to stop their vehicle. Sixteen 3-metre wide electronic two-lane roads were used, comprising a fixed set of curved road segments representing high (130 metre), medium (250 metre) and low (340 metre) curvatures and straight sections. Using different sequences of the curve segments for each road produced a set of roads with unique geometric characteristics yet presenting essentially the same driving conditions and demands.

During the trial, responses to the auxiliary task were made using two foot switches located on the floor to the left of the brake pedal. The auxiliary task was self-paced and subjects were trained to keep the error rate below 5%. Subjects were instructed to perform both the auxiliary task and the driving task to the best of their abilities but to give priority to the driving. A control condition was used to estimate the relative contribution of physical and cognitive competition. In the control condition, the subject was asked simply to look at the CRT whenever possible. Pre- and post-test trials were run to obtain single-task driving baselines. A total of thirty (10 in each of 3 groups) young, healthy male and female students with a minimum of three year's driving experience participated in these studies. The subjects received extensive training under single and dual task conditions the day preceding the experiment.

Each group of subjects represented a 6X4 repeated-measures data module (6 levels of treatment included four levels of auxiliary task load, a control condition and single-task baseline; 4 levels of driving load). Eleven dependent variables provided measures of driving performance (time to line crossing, std. dev. lane position, lane exceedence ratio, std. dev. headway, braking reaction time, velocity and std. dev. velocity), attentional behaviour (look frequency, viewing ratio and dwell time) and auxiliary task performance (correct reaction time). These measures were sampled at the rate of 20 Hz. throughout the trial. In addition, the NASA multidimensional Task Load Index technique was used to obtain subjective measures of workload at the end of each trial. The data for each trial were grouped by curve type and gaze direction and the resulting statistics were subjected to a variety of statistical analyses using SAS repeated measures procedures.

In the first experiment, a spatial perception task was used to investigate the effects of auxiliary task difficulty and driving difficulty on drivers' attention and performance. The spatial perception task required subjects to search a random field of short vertical lines for a slightly shorter target, which was present in 50 percent of the trials. Auxiliary task difficulty was manipulated by varying the number of distractor stimuli. Driving difficulty was manipulated by changing road curvature.

Performance decrements for concurrent task conditions relative to single-task driving ranged from 14% (for time to line crossing) to 26% (for std. dev. lane position). Driving load had a more pronounced effect on the data than auxiliary task load. Under concurrent task conditions, increasing driving load led to a significant decrease in time to line crossing and the various measures of attention ($p<0.01$). Increasing auxiliary task load led to a small, but significant, increase in headway ($p<0.01$). A significant interaction between driving load and task load was observed for viewing ratio.

The second experiment examined the role of auxiliary task resource structure. The second group of subjects performed a verbal memory task, based on the Sternberg paradigm, which required less sharing of resources with the driving task than the perception task. The procedures were identical to those used for the first group. The combined data yielded a mixed design in which the between-groups factor was auxiliary task resource structure. With one exception, no significant main effect or interactions involving resource structure was found. The observed interaction between resource structure and driving load for look frequency is explained by differences in display legibility. The results failed to support Multiple Resource Theory predictions, indicating that the nature and extent of intrusion were relatively robust with respect to task resource structure.

The third experiment examined the effects of auxiliary task utility. The subjects in the third group received monetary rewards depending upon their performance on the memory task. In all other respects, the procedures were identical to the second group of subjects. Hence, the combined group two and three data yielded a 2X6X4 mixed design. The analyses failed to uncover any significant main effect or interactions involving task utility. The results provide no evidence that the payment of bonuses was effective in shifting relative resource allocation between these tasks.

The results of these experiments lead to the following conclusions:

- The presence of auxiliary tasks can intrude on driving and divert a significant amount of attention away from the driving task despite appropriate task prioritization and influence of adaptation mechanisms.
- Driving load was the predominant factor affecting attention and performance.
- Auxiliary task difficulty, resource structure and utility had relatively little effect on attention and performance variables.
- Task intrusion was attributed primarily to physical mechanisms rather than to competition for cognitive resources.
- Measures of attention were more sensitive to driver workload than measures of driving.
- Attention variables reflected different aspects of task sharing.
- Simulation is a sensitive and reliable technique for evaluating joint performance with auxiliary displays.
- Driving with auxiliary visual displays can be adequately described by undifferentiated capacity models of attention.
- Further research suggested to explore (a) the interrelationships among attention variables, (b) individual differences due to age, sex and experience, (c) driver readiness to respond to unexpected events, (d) effect of imposed task pacing, and (e) the potential benefits of HUD's and auditory displays.

2. INTRODUCTION

2.1. PURPOSE OF THE STUDY

Driver interfaces are undergoing rapid technological evolution following advances in microprocessors and artificial intelligence. The present study was initiated to investigate the human factors of auxiliary automobile displays with a view towards determining the need for design guidelines. Auxiliary in-vehicle displays are defined as panel-mounted, computer-driven electronic displays which present information to the driver that is not directly required for the performance of the driving task. Auxiliary displays are being conceived and developed to extend the functionality of the driver interface beyond current capabilities. They will display information to the driver that will support auxiliary tasks. The term 'auxiliary' has been adopted throughout to distinguish auxiliary tasks from 'secondary' or 'subsidiary' tasks because the latter have specific meanings within the realm of the behavioural sciences. Auxiliary tasks are not loading tasks by design - they are actual tasks to be performed by a driver while driving. Examples of auxiliary in-vehicle displays include multi-function CRT's capable of displaying area maps, and touch sensitive controls for radio, communications and other systems.

The focus of this research was directed at visual (as opposed to auditory or tactile) displays owing to the central role of visual attention in driving. Visual displays in automobiles can be used to communicate complex driving-related information as well as information supporting tasks unrelated to driving. Indeed, driving-critical information is obtained directly from the external environment, not the dashboard.

The impact that such displays will have on traffic safety is largely unknown, giving rise to three areas of concern. The increased quantity and density of visual information may lead to longer fixations (dwell time) inside the vehicle due to longer searches as well as to a greater potential for distracting the driver due to increased display clutter and activity. The extended functionality of displays may lead to a diversion of the driver's attention away from the driving task. Poor driver adaptation to increased display intelligence and the inefficient procedures for interacting with hi-tech displays may impair the driver's ability to select and execute the most appropriate response in a timely manner. Existing ergonomics guidelines for the design of displays and controls have been adapted for automotive applications (Galer and Simmonds, 1984). However, Canadian vehicle safety regulations do not adequately address the human factors concerns arising from these emerging technologies.

The purpose of the research was two-fold. First, the study was designed to examine the relationship between drivers' visual attention and performance under concurrent multitask conditions in order to assess the need for ergonomics guidelines for the design and use of such displays. A central question was whether the presence of tasks which are likely to be presented on in-vehicle computer-based displays could cause drivers to pay insufficient attention to the road. Second, it was important to demonstrate and test methodology that could be used to evaluate the intrusiveness of auxiliary displays on driving. Technology is diversifying and advancing more rapidly than it is possible to generate appropriate design criteria. It is hoped, however, that a standardized evaluative methodology can be developed that can be implemented early in the design process to optimize interface configurations or to ensure adherence to minimum performance criteria.

2.2. DEVELOPMENTS IN DRIVER INTERFACE DESIGN

Technological advances in microelectronics, artificial intelligence and display hardware are likely to have a profound impact on the function and design of future driver-automobile interfaces. Since the first introduction of an electronic digital display in the 1978 Cadillac Seville, numerous different display technologies (including LCD and transflective LCD clusters, monochromatic and colour CRT's, vacuum fluorescent displays, etc.) have been introduced into the driver interface (Hucho, 1984; Wilhelm, 1987). The successful introduction of flat panel displays paved the way for the introduction of display intelligence. Prior to 1986, the use of microprocessor technology served primarily to enhance the functioning of certain automotive subsystems. More recently, it has been extended to enhance the driver interface, for example, in providing fuel/distance predictions, automatic headlight controls, etc.

Motivated by a need to improve product competitiveness, automobile and component manufacturers are exploring new technologies (in microprocessors, artificial intelligence and display hardware) for opportunities to respond more quickly and fully to perceived consumer demand for enhanced interface aesthetics, improved overall system performance and increased driver productivity. The demand for increased driver productivity refers to the desire to extend the functionality of the driver workstation to permit auxiliary tasks (i.e., tasks not required for the performance of the driving task). Some movement in this direction has already begun with the introduction of the cellular telephone. It is not difficult to conceptualize the transformation of the simple on-board telephone into an integrated interface with the capability for voice-based text processing, human and electronic communications, work planning and scheduling and a host of other "office" functions - the 'mobile multi-purpose interface'.

Concurrent with the development of computer-based electronic displays, technological advances in compact digital databases and position referencing systems have led to the first generation of automobile navigation systems (Thoone et al., 1987; Tomkewitsch 1986; Tsunoda et al., 1986). The productivity and safety benefits of on-route route guidance (Armstrong, 1977; Brown et al., 1986; Jeffrey 1981) have stimulated the development of several viable methods for integrating and displaying route guidance information inside the vehicle (French, 1986; Hall, 1986; Harris and Bridges, 1989; Jeffrey et al., 1987). The ETAK's navigation system, for example, is based on an improved dead-reckoning system while Chrysler's CLASS system will employ the U.S. Navy's Global Positioning System (Knoernschild, 1986) to obtain vehicle position information. Combined with the reception of traffic advisory transmission from centralized control centres, navigation displays will be able to provide real-time route guidance in response to changing traffic and/or weather conditions. Other related technologies are also advancing rapidly, most notably in the area of communications (OECD, 1987) which is expected to facilitate the transmission of traffic data and information. The realization of the ultimate goal - that is, the linking of "smart vehicles" with "smart highways" to provide for complete automation of the driving task - depends upon the development of appropriate communications infrastructure and protocols. Notwithstanding the current infeasibility of complete automation of the driving task, it is clear that the next few decades will see an accelerated growth in driver interface intelligence. This trend is reflected in the proliferation of electronic instruments and devices appearing on the dashboards of concept cars produced by the automobile manufacturers. General Motors projects that the use of electronic components will quadruple by the year 2000, from a current investment level of $500 per automobile to $2,000 (Wilhelm, 1987).

The development of intelligent driver interfaces will be accelerated due to the establishment in Japan, Europe and the U.S.A of cooperative arrangements among industry, government and academia. In Japan, for example, a large-scale research and development effort is coordinating the development of an 'Automotive Traffic Information Communications System', comprising an in-vehicle navigation system and a communications network for transmitting traffic and other information between vehicles and information processing centres. In Europe, a unified multi-national effort, coordinated under project PROMETHEUS, has been initiated to ensure product (e.g., vehicle-highway communications infrastructure) compatibility, and perhaps even standardization, within the European continent. In the U.S., a group of universities known as 'Mobility 2000' is organizing centres to coordinate R&D efforts related to 'intelligent vehicle-highway systems' (Harris and Bridges, 1989). In addition, government-sponsored projects and demonstrations are underway to investigate issues related to the integrated road-vehicle information and control systems.

Although these separate activities differ with respect to the selection and use of supportive technologies, they share similar fundamental objectives and system concepts. The primary objectives include improved traffic safety, increased highway throughput, reduced travel time, reduced fuel consumption, reduced environmental contamination, improved trip planning and driver support. Several secondary objectives appear to play an equally important role in motivating these major initiatives, including market competitiveness and the further advancement and commercialization of supportive technologies.

While the transformation of a driver workstation into a mobile multifunction interface may appear somewhat far-fetched at the present time, less-radical design 'enhancements' are presently on the drawing-boards, if not on the assembly plant floors. The evolution of the driver interface is now at the point that electronic displays are linked to on-board computers. It is awaiting the application of artificial intelligence to provide the next major technological milestone.

2.3. THE ROLE OF HUMAN FACTORS

The growing intelligence of driver interfaces may offer important opportunities to enhance safety, improve driver comfort and convenience and reduce travel time and fuel consumption.

However, the extent to which new technology can deliver such benefits depends primarily on the ergonomic design of the interface. To date, ergonomic considerations in the design of displays have been limited to the traditional issues of visibility and legibility (Galer, 1984; Galer and Simmonds, 1984; Fowkes, 1984). In addition, some of the ergonomics specifications that have been developed for electronic aircraft displays (Snyder and Bogle, 1984) may be directly transferrable to road vehicles. However, a broader view must be taken of the functional interface to ensure that the designer's approach to human/machine function allocation, does not place perceptual, cognitive and motor demands on the driver that are beyond the capabilities of the driver-vehicle system (Rouse and Cody, 1986). Interestingly, new technology does not introduce unique or unusual problems - it merely extends the scope of possible design solutions. Expressed differently, traffic safety is neither necessarily enhanced nor necessarily degraded by new technology per se. Rather, it is the form and manner in which new technology is implemented that matters. Unfortunately, the knowledge-base required to support function allocation and other decisions relevant to the design of driver interfaces is virtually non-existent. This has not proven a major problem heretofore because of the relative simplicity of conventional interfaces. However, the growing complexity of the driver interface makes imperative the conduct of theoretical and applied research in driving in order to fully exploit the potential of new technology and to avoid undesired or unwitting effects.

2.4. HUMAN FACTORS ISSUES

Analysis of the human factors issues surrounding the use of auxiliary displays logically begins with an analysis of the driving task in terms of the skills and knowledge required to perform individual components of the task. Numerous descriptions of the driving task can be found in the literature (Godthelp, 1984). Some of these are simply compilations of subtasks that drivers perform while operating a motor vehicle (Bishop et al., 1975; McKnight and Hundt, 1971). Others describe the driving task in terms of hierarchical goals (Allen et al., 1971). Others still describe the driver's behavioural response to a multitude of vehicle/road/environment conditions (Hulbert, 1984). A rich literature exists on driver, vehicle and environmental factors underlying performance of the driving task (Miller et al., 1983), including the effects of personality factors (McGuire, 1976; McKena et al., 1986), driver cognitive ability (Dewar and Lim, 1987), driver age (Staplin et al., in press), driver sex (Hagen, 1975), driving experience (Blaauw, 1982; Blaauw et al., 1977; Mourant and Rockwell, 1972), driver fatigue (Kaluger and Smith, 1970), driver stress (Moray and Smiley, 1984), vehicle handling (Hoffman and Joubert, 1966), road characteristics (Harms, 1986; McDonald and Ellis, 1975), and traffic density (Macdonald and Hoffman, 1980). A review of this literature is beyond the scope of this study. Clearly, no comprehensive definition of the driving task has been able to satisfy the diverse interests of transportation researchers. The particular approach that is taken reflects the specific needs and interests of the researcher. These can range from deriving cybernetic man-in-the-loop models (Allen and Weir, 1984; Baxter and Harrison, 1979; Blaauw, 1984; Blaauw et al., 1983; Donges, 1978; Garrot et al., 1982; Godthelp, 1986; Kroll, 1971; McRuer et al., 1977; Reid, 1983) to studying the visual basis for vehicle guidance through analyses of drivers' eye movements (Ceder, 1977; Cohen, 1978; Kramer and Neculau, 1986; McLean and Hoffman, 1973; Mourant and Grimson, 1977; Neculau et al., 1986; Senders et al., 1967; Shinar et al., 1977; Zwahlen, 1982; Zwahlen, 1985).

There are, nonetheless, some general principles of which there is widespread acceptance. For example, it is recognized that the driver perceives, processes and acts upon information that is acquired primarily from the visual modality (Dewar, 1984; Kramer and Rohr, 1982: Hartmann, 1970). It is also generally agreed that the driving task is a relatively complex perceptual-motor task which comprises numerous subtasks. The primary subtasks (those that directly contribute to vehicle control) generally fall within three broad categories; (1) lane keeping, which subsumes a variety of tracking-related task elements designed to maintain the vehicle's desired lateral position, (2) longitudinal control, which subsumes task elements designed to achieve desired vehicle speed and longitudinal position, and (3) obstacle avoidance, which subsumes task elements designed to avoid collisions with other road users or objects. Finally, it is believed that driving is normally a forgiving task which accommodates a wide range of skills and behaviours, that there are brief periods of high attentional demand and that situational demands fluctuate enormously and can change rapidly.

It is, therefore, necessary to consider potential human factors issues within this general framework. The most salient impact that auxiliary displays may have on the driving task may be the introduction of a new set of subtasks to augment the existing subtasks associated with lateral and longitudinal tracking and obstacle avoidance. This new subtask category will entail the direct or supervisory control of the hi-tech interface, involving such subtask components as monitoring, searching, reading and transforming data. It is anticipated that qualitative changes in the nature of the driving task will place greater emphasis on perceptual-cognitive subtasks. While, in the short term, traditional components of the task will remain largely unchanged, the shift towards greater perceptual-cognitive demands originating from tasks within the vehicle may result in increased driver workload (Dewar, 1988) and inappropriate driver actions, leading potentially to a greater risk of collision.

By far the majority of current research on advanced information technology and automation is directed towards the development of integrated cockpit displays. While important basic differences exist between the driving task and the flying task, it is instructive to take notice of some of the human factors issues that have emerged in advanced aircraft environments. In general, the current sentiment among human factors experts seems to be that the advent of intelligent displays and control automation has resulted in significant increases in perceptual and mediational load, subjective mental workload and stress on the part of operators (Hart and Sheridan, 1984; Kessel, 1986). There also appears to be growing concern over inconsistent demands (e.g., demands incompatible with operator capabilities, or arising from misinformation or lack of support at the crucial moments when support is most needed) that may be placed on operators of sophisticated, often partially-automated interfaces (Wiener and Curry, 1980). The extent to which this hi-tech syndrome might extend beyond the flight deck is not clear, though there is some evidence that it extends to industrial (process control) applications.

Within the context of driving, increased interface intelligence underscores a variety of human factors issues such as: (a) the increased quantity and density of information may lead to longer in-vehicle eye fixations due to longer display searches as well as to a greater potential for distracting the driver due to increased display clutter and activity; (b) the extended functionality of displays may lead to driver overload or a diversion of the driver's attention away from the driving task; and (c) poor driver adaptation to increased display intelligence and the inefficient procedures for interacting with hi-tech displays may impair the driver's ability to perform the driving task adequately.

Recent research (Dingus et al., 1988; Zwahlen and DeBald, 1986) suggests that the most urgent human factors question is whether increased competition for visual attention will result in increased risk of inattention errors playing an even greater role in accident causation than the current estimate of 30-50% (Sussman et al., 1985; Treat et al., 1979). Further reductions in drivers' attentional performance (by disrupting normal search patterns) could potentially have very serious ramifications for traffic safety. Related questions concern the extent to which specific characteristics of the displayed tasks (the auxiliary tasks), such as resource structure (Wickens, 1984) and difficulty, have on drivers' attentional response and performance.

2.5. DRIVER INATTENTION

Driver inattention is generally recognized as a major contributor to traffic accidents. In a survey of several studies of the causes of accidents, Zaidel et al. (1978) observed that reported frequencies of inattention errors were remarkably consistent across several studies despite the lack of consistency in the definition of driver inattention and the widely varying methodologies employed to investigate it. The review performed by Zaidel et al. indicated that inattention, in its broadest sense, including improper lookout, misperception and distractions, etc., was involved in 25-50% of accidents.

Unfortunately, researchers, enforcement officers, officials, accident investigators, engineers, and the public are inconsistent in their understanding and use of the term 'inattention'. The ambiguity is further exacerbated by the lack of a unified psychological theory of attention. Despite decades of research and the emergence of several theories, the attention mechanism, its form, locus and function, remains inextricable from other cognitive mechanisms.

Important as cognitive-theoretic considerations may be, from a traffic safety viewpoint, it may be pragmatic to define 'inattention' simply as a lack of awareness of critical information (such as a pedestrian crossing the road, a traffic signal, or a decelerating vehicle).

Sussman et al. (1985), in a comprehensive analysis of 1982 accident data from the U.S. National Accident Sampling System, found that 38% of drivers that had been involved in automobile crashes failed to initiate any pre-crash avoidance manoeuvre (when such action might have avoided the crash or reduced its severity), suggesting that they were unaware of the impending crash.

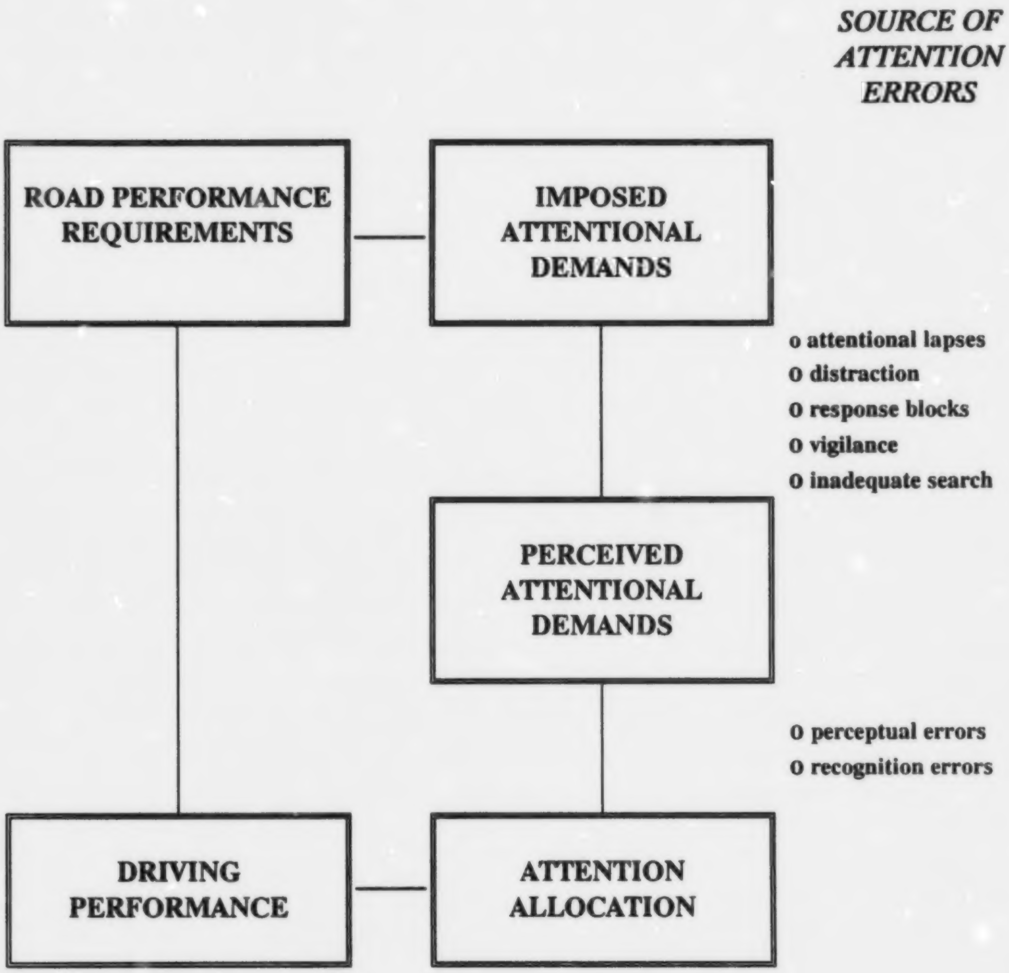
Lack of awareness can result from a failure to visually fixate on a critical object, a failure to perceive it or a failure to recognize its criticality. Zaidel et al. (1978) attributed inattention errors to a mismatch between the driver's attentional performance and situational demands. According to Zaidel et al., inattention is the "inappropriate or insufficient attentional behaviour relative to the attentional demands of the situation in which a person is performing". This definition includes both lapses in attention due to mind wandering and recognition failures due to improper lookout, distraction, or misperception. This post-facto definition is not conducive, however, to identifying and addressing the root causes of inattention errors. As a starting point, it is important to identify and examine the mechanisms that contribute to the production of inattention errors.

Figure 1 is a modified version of the model of Zaidel et al. of attentional demands and attentional performance in driving. We have attempted to distinguish among imposed attentional demands, the demands perceived by the driver and the actual attention resources allocated by the driver. The figure also illustrates that there are numerous sources of inattention errors which can arise at different stages of the attention allocation process. The errors listed are not necessarily mutually exclusive nor is the list intended to be exhaustive.

A mammoth tri-level investigation of the causes of traffic accidents (Treat et al., 1979) revealed that recognition errors were far more prevalent than driver decision or performance errors, definitely contributing to 41% of all accidents and probably involved in 56%. The study also cited improper lookout (or lack of proper visual search) as the most frequent driver error, contributing to 18-23% of accidents. This was followed by speeding (8-17%), inattention (e.g., attention lapses, 10-15%), improper evasive action (5-13%) and internal distraction (6-9%).

This evidence suggests that the most urgent human factors question is whether a proportionate shift of visual attention inside the vehicle will result in increased risk of inattention. Further reductions in drivers' attentional performance (by disrupting normal search patterns) could have serious ramifications for traffic safety. Drivers with attentional or information processing deficits may be most affected. In a comprehensive study investigating the relationship between a large number of individual psychomotor, intelligence and personality variables with the accident experience of bus and train drivers, Hakkinen (1976) reported the strongest predictor to be performance on attention-related tasks. Other studies have also found strong relationships between information processing capability and accidents (Avolio et al., 1985; Dewar and Lim, 1987; Kahneman et al. 1973; Lim and Dewar, 1988).

Figure 1: Attention and Performance in Driving


SOURCE OF ATTENTION ERRORS
ROAD PERFORMANCE REQUIREMENTS
IMPOSED ATTENTIONAL DEMANDS
o attentional lapses
o distraction
o response blocks
o vigilance
o inadequate search
PERCEIVED ATTENTIONAL DEMANDS
o perceptual errors
o recognition errors
DRIVING PERFORMANCE
ATTENTION ALLOCATION

It is therefore important to determine how auxiliary displays affect drivers' attentional performance and, more specifically, to identify the major contributing factors. Hence, in the present research a major objective was to relate changes in drivers' looking behaviour to characteristics of auxiliary displays. If attentional behaviour is governed solely by the situational demands of the driving environment then we would not expect to observe changes in looking behaviour. If, however, the results suggest that auxiliary displays can draw attention away from the driving task then it would be important to establish the conditions under which this is likely to occur and whether the effect is large enough to increase the risk of accident involvement.

Two key questions arise; "What resource demands will auxiliary displays place on the driver?", and, more importantly, "How might these demands affect the driver's allocation of visual attention?" At this early stage in their development, it is not possible to foretell the exact nature or function of future intelligent displays. The nature of future tasks subserved by auxiliary displays is still a matter of speculation at present, though a number of generic task elements can be deduced. For example, drivers may be required to (a) monitor displays to check the status of vehicle functions, (b) search pictorial and text displays, (c) read text (d) perform linguistic manipulations (e) perform spatial transformations such as rotations and comparisons, and (f) perform mathematical operations. We shall refer to these perceptual-cognitive activities as auxiliary tasks (though, in fact, they may be component elements of more complex tasks) because they are not directly required for the control of vehicle lateral position or velocity (i.e., the primary tasks in driving). Different auxiliary tasks may potentially have differential effects on drivers' attentional behaviour, depending on such factors as resource structure and the degree to which they compete with the driving task for common resources. For a given task, other characteristics such as task difficulty may also affect drivers' allocation of attention. Hence, it may ultimately be necessary to explore the drivers' attention response surface over the range of possible auxiliary tasks.

It is equally important to develop a better understanding of the mechanisms underlying the relationship between attention allocation and driving performance. The model shown in Figure 1 indicates that the allocation of attentional resources to the driving task depends upon the driver's perceptions of the momentary demands of the driving task. But, attention and performance are both elements of a closed-loop process. Attention and performance should therefore be investigated together in order to obtain a better understanding of their interdependency.

2.6. THE EFFECTS OF AUXILIARY TASKS ON DRIVING

A review of the literature relevant to the problem of time-sharing while driving was performed to identify methodological concerns and practices common to dual task studies of driving as well as to consolidate research findings that can be generalized to auxiliary display applications (Noy, 1987). The studies reviewed shared a common general research methodology, yet they represented a diversity of approaches to a variety of research problems. Because of lack of consistency in experimental protocols and the choice of dependent and independent variables, it was not possible to consolidate the findings to form a clear understanding of the mechanisms underlying driving performance under dual task conditions.

Moreover, upon further review, it became apparent that more fundamental issues existed than simply incommensurate data. Issues relating to the nature and measurement of cognitive mechanisms and time-shared performance have not yet been satisfactorily settled. Theoretical issues such as whether time-sharing occurs as parallel or serial processes bear heavily on the design of experiments and the interpretation of results. The studies examined drew from a diversity of theoretical models, often mutually incompatible, of human information processing with apparently little regard for the limitations of the underlying theory.

Nonetheless, some early studies (Brown, 1965; Brown et al., 1967; Brown et al., 1967) found that secondary tasks can have adverse effects on at least some aspects of driving when they are performed concurrently with driving.

Research directed at the effects on driving performance of the use of electronic in-vehicle displays is sparse indeed. In a recent field study, Snyder and Monty (1986) tested four prototype automobile touch-screen displays. They reported that lane keeping, speed control and braking frequency were significantly affected by concurrent performance of CRT-related tasks (which required visual feedback). The experimenters also observed significant age and sex effects. However, methodological constraints did not permit generalizing the findings beyond the specific conditions of the experiment. In particular, display/vehicle confounding and lack of systematic manipulation of experimental variables did not permit detailed analyses of the effects of specific task parameters or even separation of the effects of perceptual and response loads.

A study directly related to the use of auxiliary displays in automobiles investigated the effect of reading text while driving (Zwahlen and DeBald, 1986). Zwahlen and DeBald found that when reading text from an in-car display, the standard deviation of lane position increased monotonically as a function of time and distance. The results were interpreted as indicating that the use of sophisticated displays and/or touch panels produce significant degradation in lane keeping performance. However, Zwahlen's study did not isolate the specific effects of 'reading' which may be quite different from other uses of a display. Also, subjects in the text reading condition were not permitted to look directly at the road. Hence, the increased variability in lane position was not unexpected. A more germane question is whether drivers would voluntarily have attended to the auxiliary task for sufficient periods to cause such extreme variability in their driving.

In a more recent study, Zwahlen et al. investigated lane position variability while inputting an eleven-digit phone number on a cellular telephone (Zwahlen et al., 1988). In this two-way repeated measures experiment two telephone mounting positions were used as well as two driving conditions. In half of the trials drivers were not permitted to look at the roadway (runway) during the dialing phase while in the other half of the trials they were permitted to look at the roadway freely. They found that standard deviation of lane position was higher for the low mounted telephones than for the high mounted telephones. Also, standard deviation of lane position was higher for the no looking condition than for the condition in which drivers were permitted to look at the roadway. In all conditions, the peak standard deviation of lane position was higher than pre-dialing levels. This study suggests that drivers performed the primary task much better when they were free to look at the road, but that their performance was still impaired by the telephoning task. Unfortunately, no control conditions were used to estimate the increase in lane position variability attributable to cellular telephone use per se (as opposed to performing some other task or no task at all).

A series of studies, performed at Virginia Polytechnical Institute and State University for General Motors, evaluated some human factors aspects of navigation tasks presented on a moving-map navigation display, the ETAK Navigator (Antin et al., 1986a; Antin et al., 1986b; Wierwille et al., 1988). These studies demonstrated that the navigation task did impose additional demands on the driver with a concomitant decrease in visual attention to the roadway. The attentional requirements of some of the navigation tasks were found to be higher than the majority of tasks associated with conventional instrument use. In the more recent study (Wierwille et al., 1988), the issue of driver adaptation was explored by analyzing attentional shifts caused by changes in driving task load, such as traffic density and road curvature. The researchers found evidence that drivers adapted to the increasing demands of the primary task by reducing attention to the navigation task. However, they also reported increased data variability at these high load levels. In other words, drivers generally displayed adaptive behaviour appropriate to the driving demand - but this was not always the case. The authors provided some possible explanations for the unanticipated high level of variance, including individual differences in perceptual style, inability to adequately measure spare capacity, inaccuracies in manipulating independent variables, etc. However, the possibility certainly exists that drivers were not always able to judge the appropriate level of attention required by the primary task or were unwilling to allocate the requisite amount of attention.

In summary, the dual task driving literature provides an inadequate knowledge base for deducing guidelines or principles for the design and use of auxiliary displays in automobiles. In general, significant theoretic and methodological problems were found to seriously threaten the construct validity of the findings. In some cases, the very theory upon which hypotheses were formulated and tested is no longer current. Moreover, very few of these studies have examined mutual interference between secondary tasks and driving to investigate the nature of the interaction and underlying factors.

However, the fact that some studies have reported interference is sufficient to establish that in-vehicle tasks do compete with driving under some circumstances. More systematic research is required to produce guidelines for the ergonomic design of auxiliary automobile displays. The review was useful in identifying directions that the present research should take.

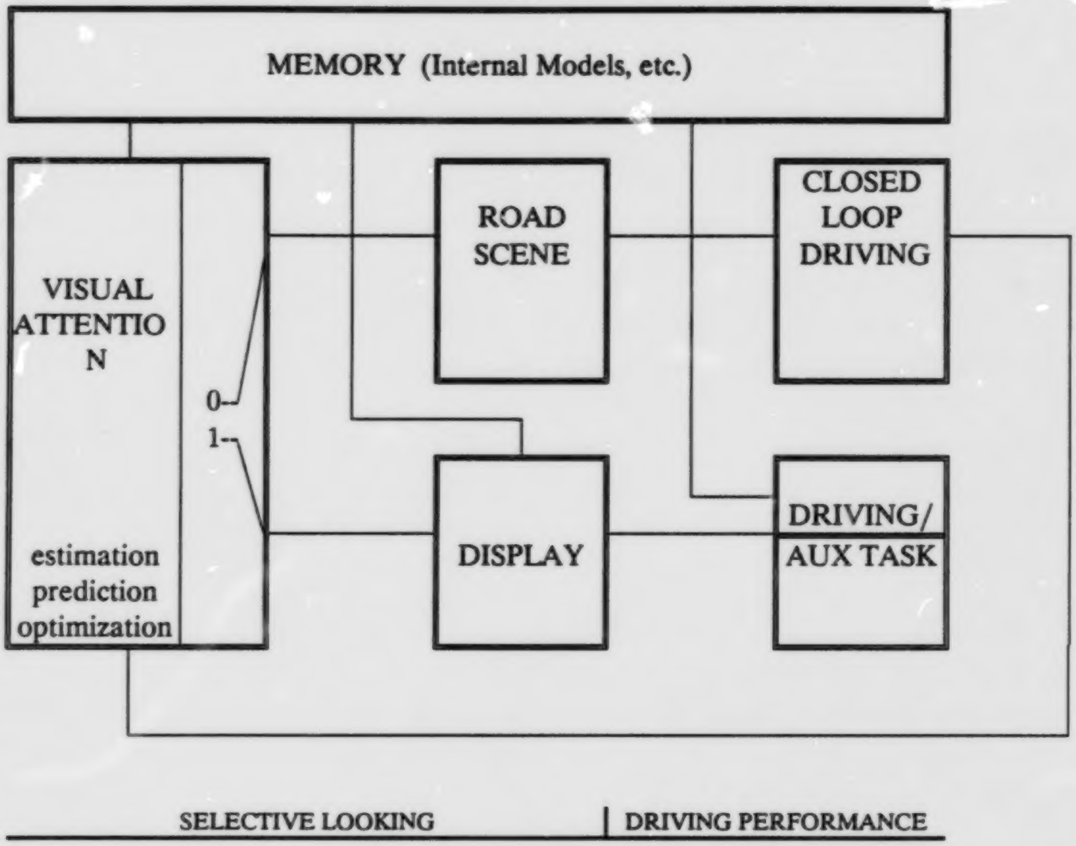
3. RESEARCH DESIGN

3.1. PROBLEM DEFINITION

The overall goal of the present research was to determine the need for ergonomics guidelines for the design of auxiliary automobile displays and suggest a method by which criteria could be developed and prototype designs can be objectively evaluated. To help formulate specific research objectives a conceptual framework was developed as depicted in Figure 2. This simplified framework is not intended as a theoretical model of driver attention and performance. Rather, it serves as a guide for considering the role of auxiliary displays in driving.

The framework comprises six elements. The central element is the attention allocation block which represents the locus of decisions about where, when and how the driver will allocate visual attention. This is consistent with the view of attention as a goal directed process. The decisions are based on predictions of future vehicle position relative to the roadway. These decisions are based upon previewed information, internalized models and individual optimization criteria for dual task performance. Attention decisions are therefore supported by memory, as shown, and, once made, are used to modify memory. The driver can either direct his/her visual attention to the roadway or elsewhere (e.g., auxiliary display). If the driver does not look at the roadway, it is assumed that attention is being directed towards some other task such as reading a display, looking at a passenger, or lighting a cigarette. Even when looking in the direction of the road scene, the driver may direct attention to irrelevant objects such as billboards (Johnston and Cole, 1976). When the driver directs attention to driving, visual cues, such as heading angle, lateral position and acceleration, are used for closed-loop control of vehicle heading and speed. When the driver directs attention elsewhere, e.g., to an auxiliary display inside the vehicle to perform another task, vehicle control is said to be open-loop since the driver does not receive visual feedback. Note that under open-loop steering, the driver does receive other forms of feedback through kinaesthetic and vestibular cues. While these sensory channels may be of limited value for the steering task, they can serve to draw attention to the roadway.

Figure 2: Conceptual Framework


MEMORY (Internal Models, etc.)
VISUAL ATTENTIO N
estimation
prediction
optimization
0-
1-
ROAD SCENE
DISPLAY
CLOSED LOOP DRIVING
DRIVING/
AUX TASK
SELECTIVE LOOKING
DRIVING PERFORMANCE

It should be noted that there are potentially two distinctly different sources of interference between driving and auxiliary visual tasks. Physical interference (often referred to as structural or peripheral interference) arises from the fact that the human visual system can only fixate on one display at any given moment. Cognitive interference arises from centralized limitations of sequential or concurrent processing of information. Although the interference effects at the cognitive level may be of greater theoretical interest, physical interference remains an important human factors problem when both primary and auxiliary displays are visual. Whilst technology might offer solutions for minimizing physical interference (e.g., through the use of auditory displays, Heads-Up Displays (HUD's), etc.) the only known technique for reducing cognitive competition between two concurrent tasks is to distribute task demands over a larger number of resources. This will be effective to the extent that joint performance is degraded by resource competition. It will, therefore, be desirable to disaggregate the contributions of physical and cognitive competition in the data and assess their relative roles in producing interference. Readers should note that the introduction of HUD's in vehicles, scheduled for some 1989 models (Dellis, 1988), may not necessarily reduce interference (Iavecchia et al., 1988; Schaeffer and Campbell, 1988) or offer drivers the benefits that have popularized the use of HUD's in the air (Roscoe, 1986; Swift and Freeman, 1986).

3.2. RESEARCH OBJECTIVES

The main goal of the present research was to determine the degree to which the performance of an auxiliary visual task might interfere with the performance of the driving task. In particular, two objectives were established; (1) to investigate the effects of auxiliary task load, resource structure and driving load on driving performance in order to assess the need for ergonomics guidelines for the design and use of such displays, and (2) to demonstrate and test a methodology that could be used to evaluate the intrusiveness of an auxiliary display on driving. A standardized evaluative methodology which can be implemented early in the design process could be a more effective countermeasure than design standards because technology is diversifying and advancing more rapidly than it is possible to generate appropriate design criteria.

To accomplish these objectives, experiments were conducted to investigate drivers' divided attention and performance under conditions in which driving was shared with an auxiliary task. The nature and degree of mutual interference under dual-task driving may be affected by task preference variables and/or subject-task variables. From a review of the current psychological literature and the results of the review of the dual-task driving literature four potentially important factors were identified: (a) the difficulty level of the driving task (b) the relative resource structure of the driving and auxiliary tasks, (c) the difficulty level of the auxiliary task, and (d) the perceived utility of the auxiliary task. For this reason, auxiliary task load, resource structure and driving load served as the independent variables.

As illustrated in Figure 2, the dual-task effects could be manifested in the attention domain and/or the performance domain. That is, the performance of an auxiliary task will likely alter drivers' visual attention patterns; however, it is not at all clear whether attentional shifts will alter driving performance. The most recent evidence suggests that drivers are able to modulate attention patterns in response to changes in driving conditions in order to minimize navigation task intrusion on driving (Wierwille et al., 1988). Hence, a critical requirement was to obtain concomitant measures of attention and driving performance.

It was also considered important to separate the relative contributions of physical and cognitive factors in producing dual-task interference. That is, if mutual interference were to be found, it would be important to determine whether the nature of the mechanisms underlying mutual interference were cognitive (e.g., competition for cognitive resources) or physical (e.g., the need to move one's head and eyes to view the auxiliary display). To test this, a control condition was used which required subjects simply to look at the auxiliary display as much as possible, without requiring any specific input or output activity.

3.3. RESEARCH OVERVIEW

Three separate experiments were performed to address the research objectives of this study. Each experiment employed ten subjects, five males and five females. The first experiment investigated the relationship between attention and performance variables under different combinations of driving difficulty and auxiliary task difficulty. The auxiliary task was a perception task that imposed demands for visual spatial resources that may be presumed to be also required by the driving task. The second study investigated the effect of altering the resource structure of the auxiliary task. The experiment was a repeat of the first experiment but a memory task was substituted for the perception task. Comparison of the results from these two experiments permitted testing hypotheses about the effect of using different types of auxiliary tasks. Multiple resource theory predicted a greater degree of intrusion from the perception task than with the memory task since the former shared more common resources with driving. Finally, Experiment Three investigated the role of task utility by introducing a reward as inducement to improve auxiliary task performance. The secondary task used for this experiment was the memory task. Comparison of the data from experiments two and three permitted testing hypotheses concerning task preferences.

4. EXPERIMENT ONE

4.1. PURPOSE

The purpose of this experiment was to investigate the effects of auxiliary task load and driving load on driving. The auxiliary task was designed to contain perceptual and cognitive elements that would compete with elements of the driving task for common information processing resources. In addition to obtaining driving performance measures, techniques were developed for obtaining quantitative measures of attentional response as intermediate variables. It was recognized that attentional response may be more acutely affected by the presence and nature of an auxiliary task than driving quality per se. That is, drivers may well experience increased workload and decreased ability to perceive or respond appropriately to events in the driving environment without a noticeable change in their ability to maintain lane position or headway. In this sense, the effects on attention may well be more critical than the effects on driving. The study of attentional response was considered paramount to developing an understanding of the mechanisms underlying drivers' response to auxiliary tasks.

4.2. METHODOLOGY

4.2.1. Experimental Design

A 4 X 4 factorial repeated-measures design was used to investigate dual-task driving performance under varying levels of primary and auxiliary task difficulty. Primary task difficulty was manipulated by varying road curvature. Senders et al. (1967) found that as the radius of road curvature decreased, the attentional demands increased. Four levels of curve type were used within each trial, namely; straight curves, 130-metre radius curves, 250-metre radius curves, and 340-metre radius curves. The second factor was auxiliary task difficulty, or more simply task difficulty. The auxiliary task was a visually-presented spatial perception task which required subjects to search a stimulus field on a computer screen and indicate the presence or absence of a target. A description of the auxiliary task appears under a separate heading. Task difficulty was manipulated by varying the number of items in the stimulus field being displayed.

A control condition was implemented in order to control for the cognitive load of the auxiliary task. In this condition, the subject was asked simply to look at the display as much as possible but not to allow the task to jeopardize driving performance. No responses were required for this condition. Hence, there was no perceptual or cognitive load. This condition permitted estimating the relative contribution of physical interference arising from the need to move one's head and/or eyes to view the auxiliary display. In order to motivate subjects to look at the display, the accumulated viewing time was displayed in the middle of the screen. Single-task driving baselines were also obtained, consisting of pre- and post-experimental trials in which subjects were required to perform the driving task alone as well as they could. For the baseline trials, no auxiliary task was presented and subjects were instructed to drive the course giving their full attention to the forward display.

There were two replications of each of 5 treatments (four levels of auxiliary task difficulty plus the control) yielding ten test trials which were counterbalanced according to a Latin Square. In addition, there were pre- and post-test trials to obtain single-task driving baselines. During these baseline trials, no auxiliary task was presented and subjects were instructed to drive the course giving full attention to the forward display.

Single task performance measures were also collected for the auxiliary task. During these trials, vehicle motion was present to control for any possible effect that motion may have on auxiliary task performance. This was accomplished by programming the computer to assume automatic control of the vehicle. Hence, the kinesthetic and peripheral visual cues were present without any of the normal demands associated with the driving task.

An important requirement for this study was the need to monitor subjects' points of regard (also referred to as fixation or gaze direction) and record these in synchrony with other performance measures. It was sufficient for our purposes simply to distinguish between glances at the roadway and glances at the auxiliary display. In order to accomplish this, an Attention Monitoring System, employing EOG techniques in conjunction with an IR-based head tracker, was specially built and tested. The Attention Monitoring System is described in the apparatus section. The availability of eye movement data (synchronized with driving and auxiliary task performance measures) permitted separating the data into two classes, one corresponding to looking inside the vehicle at the auxiliary display ('inside' condition) and the other corresponding to looking at the roadway ('outside' condition).

4.2.2. Experimental Set-Up

The experiment was performed using the Flight Research Simulator at the University of Toronto Institute of Aerospace Studies (UTIAS). A simplified sketch of the experimental set-up is shown in Figure 3. The central element was the cab of the simulator. It was mounted on a 6 degree-of-freedom motion base. The subject sat in a seat facing the rear of the cab. The driver's workstation contained all of the controls required to operate the vehicle, such as steering wheel, brake pedal and accelerator. In addition, two auxiliary task response pedals were installed to the left of the brake pedal with sufficient separation to permit the subject to rest the left foot comfortably between them. Directly in front of the driver was the optical system used to collimate the roadway images projected from the high-resolution colour monitor. The optical system provided a 30 degree (vertical) by 40 degree (horizontal) field of view. The 305-mm video monitor used for presenting the auxiliary task was installed on the instrument panel to the right of the driver and below the dash. The head tracker transducers were mounted on the top surface of the dash, one directly in front of the driver, the other about 12 inches to the right. Components of the Attention Monitoring System were located in the seat pocket behind the seat.

All of these systems and devices were interfaced to the Perkin-Elmer computer which computed the dynamic vehicle response in real time and controlled the various subsystems. The experimenter's station comprised one terminal for communicating with the Perkin-Elmer, another terminal for displaying outputs from the Attention Monitoring System, a CCTV monitor for observing subjects' looking behaviour, an oscilloscope for monitoring EOG and head tracker signals and an intercom for communicating with the subject. In addition, other elements of the system which required experimenter control, including power switches for cab lighting, sound generator controls, force feedback system, motion base controls and the IRIS computer and keyboard were located adjacent to the experimenter's workstation.

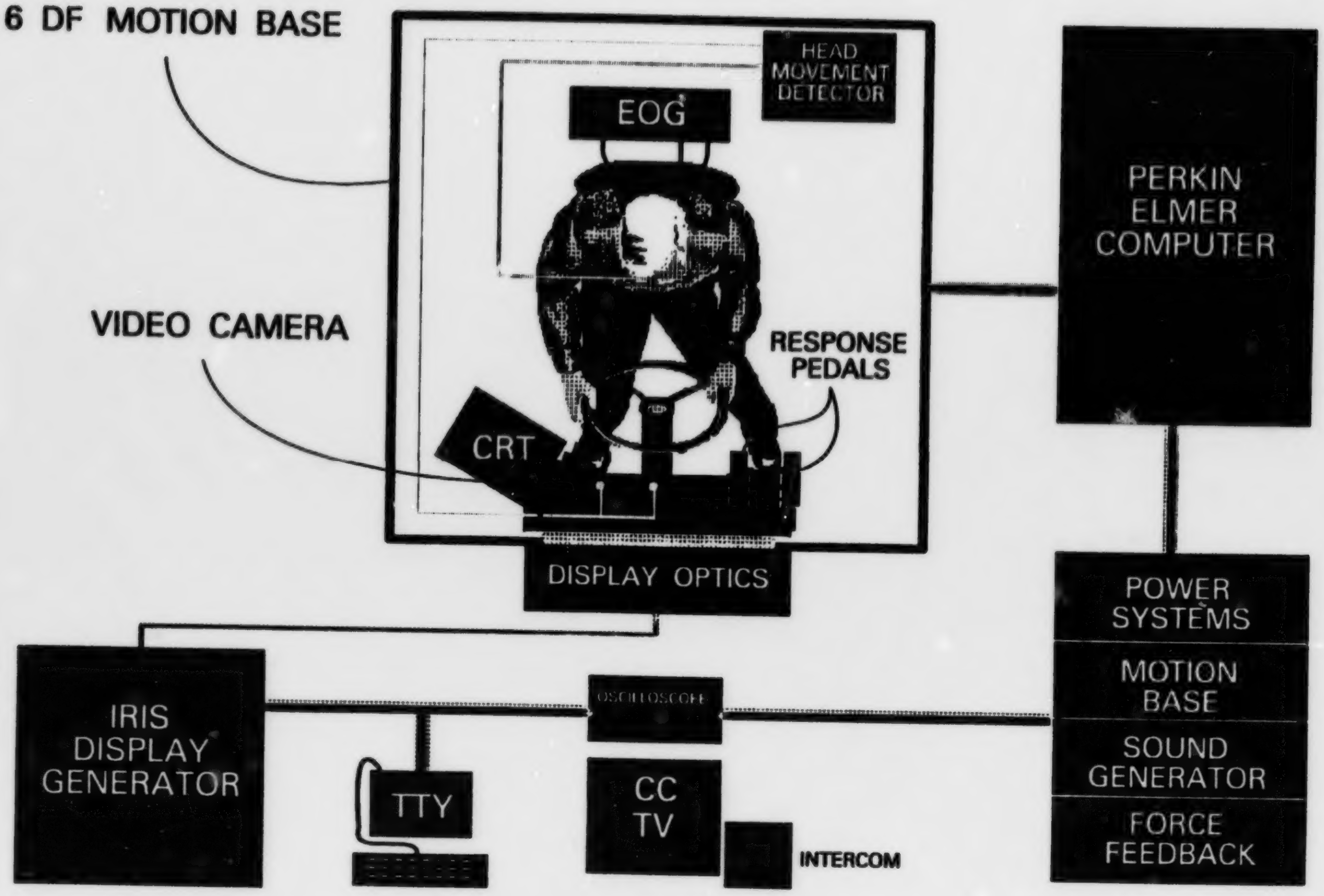

6 DF MOTION BASE
VIDEO CAMERA
HEAD MOVEMENT DETECTOR
EOG
RESPONSE PEDALS
CRT
DISPLAY OPTICS
PERKIN ELMER COMPUTER
POWER SYSTEMS
MOTION BASE
SOUND GENERATOR
FORCE FEEDBACK
IRIS DISPLAY GENERATOR
OSCILLOSCOPE
TTY
CC TV
INTERCOM

Figure 3: Experimental Set-Up

4.2.3. Apparatus

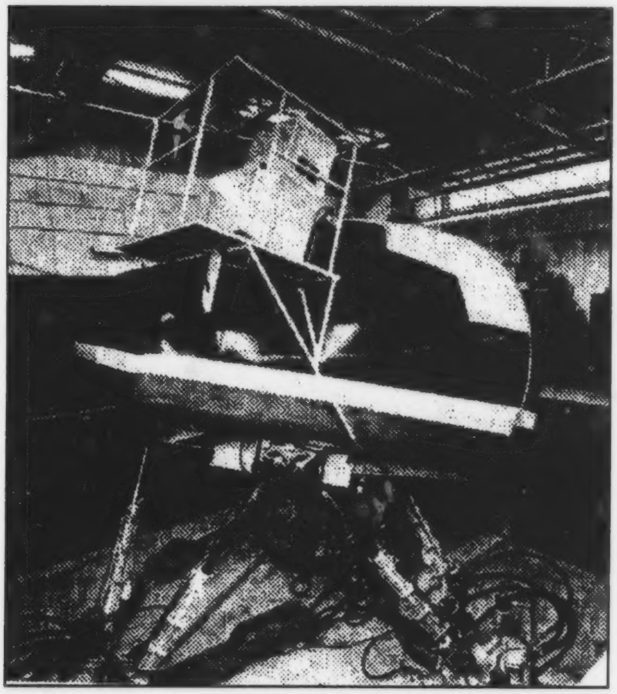
4.2.3.1. UTIAS Flight Simulator

The Flight Research Simulator at the UTIAS, shown in Figure 4, is a mock-up of a DC-8 cab mounted on a CAE Series 300 hydraulic-actuated synergistic motion-base which is capable of motion in six degrees-of-freedom (surge, sway, heave, pitch, roll and yaw). The rear section of the cab was configured as a driving workstation representing a conventional compact-size vehicle. Figure 5 shows the rear workstation which contained a seat installed in front of the automobile dashboard as well as all of the controls required to operate an automatic transmission vehicle, including accelerator pedal, brake pedal and steering wheel. The facility also includes a visual system, a computer, and other subsystems such as a sound generator, and a control loading system that was used to apply load forces on the steering wheel.

Driver actions - accelerator pedal deflection, brake pedal deflection and steering wheel angle - served as inputs to a set of vehicle equations of motion needed to determine vehicle dynamic response at a given point in time. A set of 51 differential equations were developed at UTIAS to define vehicle motion. The motion characteristics of the simulator had been previously documented (Grant, 1986). The command signals were attenuated and then passed through a set of washout filters designed to produce smooth simulator response over the range of travel of the actuators (Wierwille, 1975). To enhance the sensation of sustained acceleration in the longitudinal axis a small amount of tilt coordination was used. The simulator was "tuned" by adjusting the attenuation and washout filter parameters to achieve maximum subjective realism.

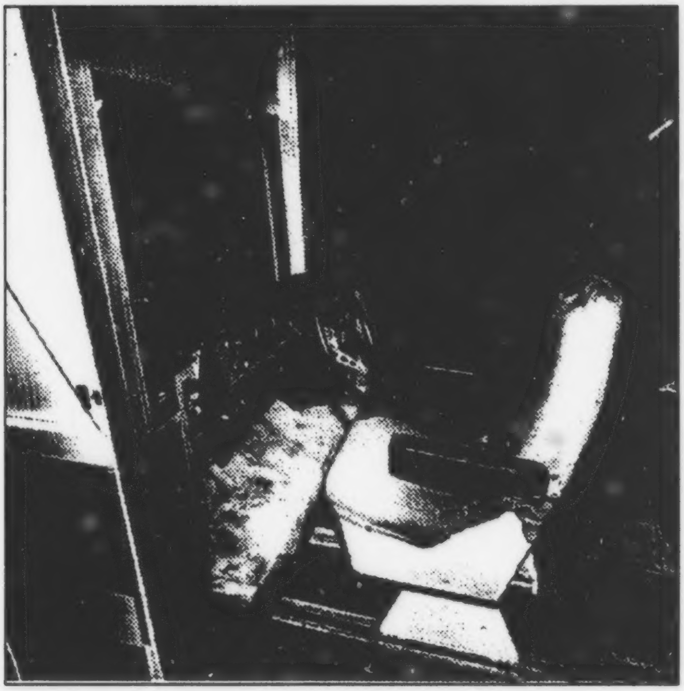
A Panasonic WV-CD22 charge coupled device (CCD) closed-circuit television (CCTV) camera was mounted on the dash above the auxiliary display. An intercom system provided communications between the subject and the experimenter who was positioned outside the cab.

Figure 4: UTIAS Flight Research Simulator



The simulator was controlled by a Perkin-Elmer 3250 32-bit digital computer. This minicomputer was used to solve the vehicle dynamic equations, generate the commands to drive the motion base and the instrument displays (speedometer), generate inputs required by the IRIS graphics computer and the BEST microcomputer used to administer the auxiliary task, and to drive the audio generator and the control force system. In addition, this computer was interfaced to the experimenter's computer terminals and served as the data acquisition system.

Figure 5: Driver Workstation



The driver's forward view of the roadway was generated on a 25-inch high resolution (1024 X 768 pixels) raster monitor driven by an IRIS 3020 colour graphics system. An optical system was used to collimate the display, giving a total field of view of about 30 X 40 degrees. Scenes were drawn for a specific set of driver's eye coordinates (transmitted from the main computer) to represent the world as seen from that position. Scene content was limited to about 300 polygons to allow a scene update rate between 20 and 30 Hz. The IRIS graphics engine performed high speed transformations and rasterizations. Graph Theoretic algorithms were implemented to deal with hidden surfaces. In addition, shading and shadowing techniques were used to enrich the scene.

A 300-mm high-resolution colour graphics monitor used for presenting the auxiliary task was installed on the instrument panel to the right of the driver and below the dash. The display was driven by a BEST microcomputer which was located on the left side of the cab. The microcomputer was interfaced to the Perkin-Elmer computer which started the task. The Perkin-Elmer accepted performance data transmitted by the BEST during the trial.

4.2.3.2. Attention Monitoring System

The Attention Monitoring System was used to determine whether the subject was looking at the forward display (roadway) or at the auxiliary display. It comprised a head tracker and an eye tracker to detect head and eye movements as well as logic software (resident in the Perkin-Elmer) to combine and interpret these data. Both component devices were found to be necessary to determine reliably fixation direction. The outputs of both devices were transmitted to the Perkin-Elmer computer for processing. The EOG signal was analyzed to detect gross shifts in eye gaze indicative of eye transitions from one display to the other. The head tracker produced a binary signal which had already been individually calibrated to indicate gross head movements away from or towards the forward visual axis. The algorithm that combined both EOG and head tracker signals to detect shifts in fixation directions permitted the experimenter to select certain parameters (such as weighting factors) to tailor the system to individual subjects' looking characteristics. When the combined signal strength exceeded threshold values, a visual transition was determined to have occurred. The transitions were either from the roadway to the auxiliary display or vice versa. The weighting factors and calibration parameters for each device were used to correct for individual differences in head and eye movement behaviour.

The detection of a transition resulted in the generation of an audible tone at the experimenter's terminal and the updating of a condition flag within the Perkin-Elmer indicating whether the subject was looking outside at the roadway or inside at the auxiliary display. In addition, the experimenter's display was updated to indicate the subject's point of regard. The visual transitions were logged by the computer in synchrony with other performance measures.

4.2.4. Experimental Tasks

4.2.4.1. Driving Task

The primary task was to drive the car over a winding road. Subjects operated the steering wheel, accelerator and brake pedals in the normal manner to control vehicle position and speed. They were asked to keep both hands on the steering wheel while driving. Subjects were instructed to maintain constant lane position. The instructions emphasized the need to minimize lateral drifting within the lane (i.e., minimizing tracking variability). In addition, subjects were required to follow a truck displayed on the road ahead of them (to be referred to as the lead truck) and they were instructed to maintain a constant headway of 50 metres (equivalent to 3 seconds at a speed of 60 kph). Colbourn et al. (1978), found that a headway of 2 seconds was adequate to avoid rear-end collisions even under emergency conditions. The car following task was adequately represented by the visual system, since headway estimates are normally made on the basis of two-dimensional spatiotemporal cues (Schiff and Detwiler, 1979).

During the experimental trials, the auxiliary task was presented on a CRT display. In order to ensure that there was sufficient opportunity for subjects to perform the auxiliary task, the driving task parameters (e.g., speed and course geometry) were selected during pilot tests to require about 50% of subjects' visual attention.

The subject was instructed to perform the auxiliary task as well as he/she could without allowing it to detract from the driving. Responses were made using two foot switches located to the left of the brake pedal. These pedals were separated by 4 inches to permit the subject to rest the left foot between the pedals between responses.

The CRT display was located on the instrument panel, approximately 30 degrees to the right of the steering wheel and about 30 inches from the driver's eyes. Selection of this location for the CRT was considered to reflect the current trend in workstation layout (Olson, 1987) and represents a compromise between two important study considerations. On the one hand, it was necessary to provide sufficient separation between the auxiliary display and the forward display to permit reliable determinations of where the driver was actually looking. On the other hand, overly large separations would reduce the amount of useful information that a driver might receive from the peripheral visual field while looking at the auxiliary display. (The detection threshold for motion in the periphery rises sharply as a function of eccentricity (Tynan and Sekuler, 1982). It has also been shown to be a function of speed of motion of the object, its direction of motion, size, spatial frequency, and contrast.)

The first three hundred metres of road in each trial consisted of a straight section used primarily to allow the driver to achieve stable initial conditions with the car traveling at 60 KPH, 50 metres behind the lead truck. At the start of each trial, the subject's vehicle was standing 50 metres behind the truck. Subjects were advised that this was the desired separation. They began by accelerating to 60 kph as quickly as possible and then maintained that speed by checking their speedometer often as they approached the 300-metre point. During this portion of the run, the truck automatically stayed 50 metres ahead of the subject's vehicle. However, at the 300-metre point, a tone was heard signalling the start of the experimental portion of the trial. At this point, the truck continued traveling at a fixed speed of 60 kph, the speedometer display was disengaged to prevent its use, and the auxiliary task was started. The subject's performance had stabilized by this point and the data recording was commenced. Each trial consisted of 4 to 6 minutes of driving and performing the auxiliary task.

Upon reaching a predetermined distance (which varied randomly from trial to trial), the lead vehicle began to decelerate rapidly. Immediately upon detecting this, the subject was required to depress the brake pedal to stop the vehicle. The trial ended with a correct brake response or a crash.

4.2.4.2. Spatial Perception Task

As indicated in the introduction, navigation displays are amongst the most complex of visual displays being developed for use in automobiles. Hence, the auxiliary task used for this experiment was designed to emulate in some ways the demands that would be imposed by map displays. Because visual search of spatial stimuli is an important element in map reading (Thorndyke and Stasz, 1980), a visual perception task encompassing spatial stimuli was considered a valid abstraction of some components of a map reading task. The task was designed to measure perceptual speed in searching and comparing symbol size characteristics, an important aspect of navigation task performance (Antin et al., 1986a; Antin et al., 1986b). Moreover, a task requiring spatial resources was predicted to compete highly with the driving task and provide a testbed for the study of mutual task interference.

The perception task required subjects to search the 305-mm CRT display for the presence of a short, vertical line (6.5 mm) in a field of 8 mm vertical distractor lines. Display intensity was adjusted by each subject for comfort and legibility in the darkened cab of the simulator. The size specifications of the target line and distractors had been established in preliminary tests to yield reaction times of about 2 seconds for tasks of intermediate difficulty (6-stimuli displays). The display presentation consisted of the predetermined number of lines placed randomly within the display screen. Positive and negative displays (presence and absence of a target) were presented with equal probability. Subjects responded to positive or negative displays by depressing the right and left foot switches respectively. Subjects were trained to keep the error rate below 5% when performing the auxiliary task. This eliminated the possibility of speed-accuracy tradeoff effects. Error rate feedback was provided at the completion of each trial and subjects were encouraged to maintain a high accuracy score.

The auxiliary task was self-paced; that is, each response triggered a new presentation. Task difficulty was manipulated by varying the number of items displayed. Four levels of task difficulty were presented, corresponding to 2, 4, 8 and 12 items. Previous research (Treisman, 1982; Treisman 1986) has shown that reaction time is linearly related to set size, the slope representing processing rate.

4.2.5. Dependent Measures

Four categories of dependent measures were obtained throughout the trial. The measures of driving performance, attentional behaviour and auxiliary task performance are listed in Table 1. In addition, the NASA multidimensional Task Load Index (TLX) technique (Hart and Staveland, 1988) was used to obtain subjective measures of workload at the end of each trial in an effort to determine subjects' response to increased demands under dual-task conditions. A description of each of these measures follows.

4.2.5.1. Driving performance

The measures of driving performance were selected from the literature on the basis that they have proven reliable and sensitive to the effects of a variety of subject-task variables, that they are appropriate within the context of the study and that they possess a degree of face validity as overall measures of the quality of driving. Snyder and Monty (1986) found that lane keeping, velocity maintenance and brake activations were sensitive to drivers' attentional demands. However, some potentially good measures were omitted from their study, most notably time to line crossing (TLC; see e.g., Godthelp, 1984 and Godthelp et al., 1984) and headway.

Standard deviation of lane position (SDLP) was the average standard deviation of the centre line of the vehicle from the centre of the lane.

Lane exceedence ratio (EXC) was the proportion of run time that any one of the vehicle tires was outside of the driving lane.

Headway (HDWY) was the distance from the front of the subjects vehicle to the rear of the lead truck.

Time to line crossing (TLC) was the instantaneous predicted time before the subject's vehicle would cross either side of the lane, assuming the steering wheel angle remained constant into the future. TLC was derived for each sampling interval by iteratively comparing future vehicle path (computed from lateral lane position, heading angle, vehicle speed and steering wheel angle) with the lane edge geometry and determining the time of crossing. Because of the high computational load, TLC calculations were performed only for the first 5 seconds of each curve. The median TLC value for this period was used. Further details of this measure can be found in Godthelp et al. (1984).

Velocity (VEL) was the average velocity throughout the run segment.

Table 1: Table of Dependent Variables

Driving Performance	
Standard Deviation Lane Position (m.)	SDLP
Lane Exceedence Ratio (%)	EXC
Time To Line Crossing (sec.)	TLC
Headway (m.)	HDWY
Velocity (m./sec.)	VEL
Standard Deviation Velocity (m./sec.)	SDVEL
Braking Reaction Time (sec.)	STOPRT
Attentional Behaviour	
Dwell Time (sec.)	DWELL
Look Frequency (1/sec.)	LFREQ
Viewing Ratio (%)	VR
Auxiliary Task Performance	
Reaction Time (sec.)	NEGRT
Mental Workload	
Task Load Index	TLX
Mental Demand	MD
Physical Demand	PD
Temporal Demand	TD
Effort	E
Performance	P
Frustration	F

Standard deviation of velocity (SDVEL) was the average standard deviation of velocity throughout the run segment.

These 7 driving measures were sampled and recorded at the rate of 20 Hz. throughout the trial. The Attention Monitoring System indicated which display, the forward visual scene or the auxiliary display, was being viewed during the sample interval. Hence, in addition to run averages for the various measures, it was possible to compute separate statistics for 'inside' (driver looking at the auxiliary display) and 'outside' (driver looking at the forward display) looking conditions. This permitted separate analyses of closed-loop and open-loop driving.

In addition to these measures of driving performance, the subject's braking response was measured at the end of each trial. Braking reaction time (STOPRT) was defined to be the time interval between the onset of deceleration of the lead truck and the subject's activation of the brake pedal.

4.2.5.2. Attentional Behaviour

Attentional behaviour was measured using the Attention Monitoring System. Three measures were obtained; dwell time, viewing ratio and look frequency.

Dwell time (DWELL) was the average duration of fixations on the auxiliary display.

Look frequency (LFREQ) was the reciprocal of the average interval between fixations (the number of fixations divided by the run time)

Viewing ratio (VR) was the proportion of the total run time that the subject looked at the auxiliary display. This measure was equivalent to the product of look frequency and dwell time.

4.2.5.3. Auxiliary Task Performance

A number of auxiliary task measures were tested in preliminary trials. These included reaction times and reaction time variances to positive (i.e., target present) and negative displays (i.e., target absent), as well as accuracy rates for positive and negative displays. The most stable measure was found to be reaction time to negative displays. Responses to positive displays were relatively less stable presumably because the subjected ended the search the moment the target was identified. Reaction time to positive displays, therefore, depended largely on the location of the target relative to the subject's search strategy. In contrast, in order to identify a negative display, the subject would have had to process each item. Accuracy rates were invariant, since subjects were required to maintain an accuracy of 95%.

Reaction time (NEGRT) was the average correct reaction time to negative displays.

4.2.5.4. Workload

Subjective measures of workload were obtained in an effort to assess subjects' response to increased demands under dual-task conditions. It has been suggested that subjective mental workload is highly correlated with the degree of timesharing required in a dual task paradigm (Navon and Gopher, 1980). The NASA multidimensional Task Load Index (NASA-TLX) technique was used to assess subjective mental workload. The technique requires assessment along six bipolar scales. The scales, which represent the possible sources of workload, include: physical demand (PD), mental demand (MD), temporal demand (TD), effort (E), performance (P) and frustration (F). The weighted combination of these ratings is computed to reduce between-subject variability.

The administration of the technique requires subjects to report subjective ratings (on a 100-point scale with defined endpoints) for each of the scales. A separate pair-wise comparison procedure is then used to derive the weighting factor for each dimension that is used in the calculation of the composite measure, TLX. The definitions and the procedures for collecting these data and calculating the composite TLX are described in more detail in Hart and Staveland (1988).

Task Load Index (TLX) was computed as the weighted average of the other bipolar scales using individually determined weighting factors.

4.2.6. Test Trial

Each test trial began with a warm-up phase (about 15 seconds in duration) in which subjects drove over a fixed-length straight stretch of road, 300 metres in length. This initial phase of the trial was required to establish uniform and stable initial conditions for the trial. The subject was required to accelerate and a attain a stable speed of 60 kph. During this initial part of the course, the lead truck automatically kept a lead distance 50 metres ahead of the subject's vehicle. Upon crossing the 300-metre point, a short medium-frequency tone was generated signalling the start of the experimental portion of the trial. At this point, the speedometer was disengaged to prevent its further use, and the auxiliary task was initiated. The subject's primary task was to keep a fixed headway and lane position. The auxiliary task was performed when it was possible to do so without jeopardizing driving performance.

The driving course was a winding two-lane highway comprising a series of curved sections as described under a separate heading below. Buildings alongside the highway provided a measure of realism to the driving scene as well as perceptual cues required for estimating distances and speeds.

At the end of the trial, the lead vehicle began to decelerate rapidly. Upon detecting this, the subject was required to depress the brake pedal and to stop behind the truck. The trial ended with the car coming to a complete stop behind the truck or with a crash. The average length of a test trial was approximately 5 minutes (it was varied from 4 to 6 minutes to prevent subject anticipation of the end of trial).

In order to be able to test for differences in response latency due to gaze direction at the start of truck decelerations (i.e., attention directed either to the primary or auxiliary display), subjects' looking behaviour was used to trigger the onset of truck deceleration. This was achieved by delaying the truck deceleration beyond the assigned trial period until such time that the Attention Monitoring System indicated that the subject was looking at the desired display. Each experimental condition was replicated in order that both types of endings (looking 'inside' and 'outside') could be presented to subjects. Hence, in half of the trials, the truck began to decelerate while the subject was looking outside at the roadway; in the other half, the truck began to decelerate while the subject was looking inside at the auxiliary display.

At the end of the trial both displays were blanked and the cab lights turned on to permit visual-vestibular reorientation. The next trial commenced a minute or two later.

4.2.7. Roads Library

Sixteen 3-metre wide electronic two-lane roads were constructed to form the roads library, each comprising a random sequence of straight and circular arc road segments with spiral transitions. A hierarchical graphics editor was used in the construction of the roads to define and modify scenes for the graphics database. The roadway scene included a dark grey paved surface with yellow lane markings. The sky was blue and the off-road terrain was green. In addition to the roadway, buildings were positioned along both sides of the road to enhance visual fidelity and provide cues to facilitate the perception of depth and motion. The buildings were solid rectangular objects which had realistic colours, including shading, and they were made to cast shadows.

Special routines were used to preprocess the roads (primarily to sort vertical surfaces within the scene) in order to reduce the on-line time needed to refresh the screen.

Each trial employed a different road. The roads presented a winding course to subjects which could be easily negotiated without requiring full attention. Fifteen roads were required for the experimental trials and one for training and practice. Each subject was exposed to all of the roads during the course of the experiment.

Road characteristics such as minimum radius of curvature, transition lengths, lane width and dimensions for lane markings were selected to conform to the geometric design standards for Ontario highways for speed limits of 60 kph (Ministry of Transportation and Communications, 1985), with the exception that there was no superelevation of the road surface (i.e., the road was flat, not cambered). Painted broken centre lines were 3 metres long, 10 cm wide and spaced at 9 metre intervals.

Seven road segment types were used in the construction of the roads; straight segments and left and right curved segments at three different horizontal radii of turn. For the design speed of 60 kph, the range of realistic turn radii is 100 metres to about 350 metres. The specific radii selected for the present study were 130, 250 and 340 metres. Each curve contained leading and trailing transition spirals to ease entry into and exit from the curve. The logarithmic spirals (i.e., transitions leading and trailing the circular arcs) had linearly changing curvatures with distance along the curve to allow smooth steering control. The total heading change (the angular difference between curve entry and exit equals the integral of the product of curvature and distance) was set to provide approximately 100 metres of road having a constant radius of curvature (i.e., excluding transitions).

To ensure that all subjects were exposed to all curves in each trial, the roads were designed in such a way that the first four kilometres of the course (i.e., the distance traveled in the shortest possible trial) contained two replications of each of the seven curves. The order of the curves over this part of the course was randomized during the construction of the 15 roads. The remainder of the course consisted of a random selection from the curves listed above. Curve segments were separated by straight road segments of random length. This measure was designed to avoid any possible carryover of effect from one curve segment to another that may be due to a lag in the driver's response. It was recognized that response lags might also affect the data at the beginning of a new curve segment; however, it was considered that the presence of leading transition lengths would reduce the extent of this problem. The only restriction to the random selection and sequencing of curves was that the resultant road could not cross itself, thus avoiding potential artifacts due to the presence of intersections. Roads that crossed themselves were discarded and replaced. A straight section of 300 metres in length was constructed at the beginning of each road.

It should be recognized that constructing roads in this way provided an elegant balance between the need for experimental control and the need for randomization of driving parameters. While each road had unique geometric characteristics, all of the roads contained the same set of curves. This technique ensured that all of the roads presented essentially the same driving conditions and demands while, at the same time, preventing any possibility that subjects could 'learn' the road.

4.2.8. Subjects

Subjects were ten young male and female student volunteers. Because of gender differences found by Hagen (1975), an equal number of male and female subjects was used in this and subsequent studies to avoid a possible gender bias and to ensure a constant male/female proportion across all of the studies. The five male and five female students were recruited from poster advertisements placed on the York University campus. Subjects ranged in age from 19-33 years, with a mean age of 23.3 years. All of them had normal vision (or corrected normal vision - contact lens wearers were rejected because the exaggerated blinking commonly induced by contact lens use was found to produce spikes or other forms of noise in the EOG signal). All of the subjects had a minimum of three years of driving experience and all owned their own vehicle. Although this sample group may not necessarily be representative of the general driving population, this group was highly familiar with the use of computers and electronic information displays and was considered representative of the group most attracted to and most likely to use such displays in automobiles. This group was also expected to be least sensitive to time-sharing effects (i.e., older drivers would be expected to show greater interference (Stein et al., 1987); hence, the results may be regarded as being conservative. Candidates with poor driving records or who had been involved in traffic accidents during the previous three years were excluded from the study.

Subjects were requested to sign a consent form indicating that they understood the nature of their participation in the experiment.

As described later in the procedures section, perceptual and cognitive tests were administered to successful candidates in an attempt to determine the potential role of cognitive and perceptual style in producing individual differences. These tests included the Embedded Figures Test (individual version) for field dependence/independence (Witkin et al., 1971) and the Contrast Sensitivity vision test, using Visitech's Vision Contrast Test System.

Each subject received nearly four hours of single and dual task training a day or two prior to testing to ensure good familiarity with the equipment and the experimental procedures. They were paid $100 for their participation in the study.

All of the subjects tested were free from any symptoms of simulator sickness. Simulator sickness (typically manifested as sweating, queasiness, dizziness, blurred vision, nausea, etc.) was experienced by three candidates all of whom presented symptoms within the first five minutes of driving the vehicle during the training session. As soon as these symptoms were detected, the training ceased and the subject was withdrawn from any further testing. None of the subjects who were prone to simulator sickness vomited, and all recovered completely after 30 to 60 minutes of rest in the laboratory.

4.2.9. Procedures

Each morning, after all of the equipment was turned on, the simulator was checked for hydraulic fluid leaks and other subsystem abnormalities. The motion system pumps were allowed to warm up to a temperature of at least 37 degrees Fahrenheit to achieve the necessary fluid viscosity before testing began.

4.2.9.1. Subject Processing and Training

After obtaining the relevant demographic information, the subject was informed about the purpose of the study and given a general overview of the experiment. He/she was then asked to sign the consent form. Prior to actual training, the subject's vision was tested for visual acuity (using a Snellen wall chart) and contrast sensitivity (using the Visitech VCTS 6500 far chart). Finally, the Witkin Embedded Figures Test was administered in accordance with the instructions accompanying the test. The preliminary phase took about 20-30 minutes to complete. The subject was then ready for training.

Each subject received extensive training in the simulator and in the experimental procedures. First, the subject was given a set of instructions which described what the subjects was required to do and what to expect during the course of the experiment. The initial set of instructions contained only portions describing driving task requirements, the proper control of the simulator, use of safety equipment and escape procedures in case of emergency. After answering any questions the subject may have had, he/she was then directed inside the simulator cab. The seat was adjusted to the subject's comfort. A two-dimensional cardboard prop with the top edge shaped to represent the driver's view of the hood of the car was propped up on the dashboard. This prop was positioned appropriately for the subject 's eye height by moving it forward or backward until the top edge was coincident with a reference line generated in the visual scene in front of the subject by the IRIS. The head band containing the head tracker transmitter was placed on the subject's head and calibrated.

The first phase of simulator training comprised a series of driving-only trials. Subjects were monitored closely on CCTV monitor for symptoms of simulator sickness. At the completion of each trial, they were asked how they felt. When they occurred, simulator sickness symptoms appeared within the first trial or two. If symptoms were detected, the experiment was stopped and the subject taken out and allowed to rest until fully recovered. No further testing occurred for these subjects.

Mean levels and standard deviations of lane position and headway were recorded and plotted at the completion of each trial to continually monitor the subject's learning rate. After completing a minimum of five practice trials, additional trials were given until performance levels stabilized.

The subject was then led outside of the simulator for a short interlude and given the next set of instructions on how to perform the auxiliary task. Only the instructions relevant to the group to which he/she belonged were given. The instructions stressed the need to obtain a minimum accuracy level of 95%. This accuracy criterion was established in order to avoid the possibility of speed/accuracy tradeoffs from affecting the data. Subjects were able to achieve this level of accuracy without the need for extensive practice.

After their return to the simulator, a series of trials were given in which the subject directed his/her full attention to the auxiliary task. During these trials, the auxiliary task was set at an intermediate level of difficulty (6 lines). For these trials, the car was programmed to drive automatically along the road in order to generate appropriate sensations of motion and noise. Again, performance (accuracy and reaction time scores) was plotted continually to obtain the subject's learning curve. Subjects were given accuracy scores, and if these fell below the 95% criterion level, they were asked to improve their accuracy. A minimum of five trials were given. Training ended after performance was observed to have plateaued. Normally five to eight trials was sufficient to achieve asymptotic levels of performance.

Again the subject was taken out of the simulator. The next set of instructions described how to perform both the driving task and the auxiliary task concurrently. The instructions stressed the driving as the primary task and the importance of performing the auxiliary task only when it was judged to be safe and not to interfere with the driving. The subject was then led to a small table near the experimenter's position. The EOG electrodes were attached to the outer canthus of each eye and the reference electrode attached behind the left ear. The eye tracker device was tested and calibrated. At this point, the subject received further instructions on the use of the subjective bipolar scales to report experienced levels of workload during the trial. The subject was then led back into the simulator and the head band containing the head tracker transmitter was placed on the subject's head and calibrated.

Four dual-task trials were given. During these trials, the Attention Monitoring System was checked and calibrated against CCTV views of the subject's eyes. Looking behaviour was easily determined from the CCTV pictures. Workload ratings were given by subjects over the intercom after the completion of each trial. At the completion of the set of four dual-task trials, the subjects completed the Sources-of-Workload Tally Sheet which was required for determining the six scale weighting factors used in computing the composite task-load index (Hart and Staveland, 1988).

4.2.9.2. Testing

The subject arrived in the lab fully trained in the experimental procedures. The EOG electrodes were attached to the outer canthus of each eye and behind the left ear and the eye tracker was calibrated. The subject was then directed to the simulator. The seat was adjusted to the subject's comfort. A two-dimensional cardboard prop with the top edge shaped to represent the driver's view of the hood of the car was propped up on the dashboard. This prop was positioned appropriately for the subject 's eye height by moving it forward or backward until the top edge was coincident with a reference line generated on the visual scene in front of the subject by the IRIS. The head band containing the head tracker transmitter was placed on the subject's head and calibrated.

The subject was then given two complete practice trials. During these trials, the auxiliary task was set at an intermediate level of difficulty (6 lines).

The formal part of the experiment was divided into two sessions separated by a 30 minute rest break. Each session lasted about two hours. The first session comprised 8 trials whereas the second session comprised 7 trials, for a total of 15 trials. The first and last trial were reserved for collecting pre- and post-experimental baseline data. The pre-experimental trial consisted of 4 consecutive one-minute blocks in which subjects performed the auxiliary task alone. The four blocks corresponded to four levels of task difficulty. At the completion of the single-task auxiliary task blocks, the subject was asked to drive a complete course in which no auxiliary task was presented. The post-experimental trial followed the same protocol but this time the four auxiliary task blocks followed the driving trial.

Three of the 15 trials were designated as 'throwaway' trials. These trials had very short durations and were included merely to prevent subjects from forming trial duration expectations. The throwaway trials always occurred as trials 2, 5 and 8 and ran for 1, 1.5 and 2 minutes respectively. No data were collected for the throwaway trials.

The remaining ten trials represented dual-task conditions. There were two replications each of 4 levels of task difficulty (eight trials) and the control condition (two trials). The order of these ten trials was counterbalanced across the ten subjects according to a Latin Square design. The experimental trials ran 4 to 6 minutes each. Curve type (or driving difficulty), of course, was varied within trials since each road contained all of the curve segments as explained earlier.

4.3. RESULTS

Three subjects were withdrawn from the experiment because they exhibited simulator sickness symptoms and consequently did not complete the testing. This incidence rate of 30% is typical for simulators of this kind (Kennedy et al., 1987) and is thought to be due primarily to delays in the visual and motion systems (Frank et al., 1987). Subjects who were withdrawn from the study were replaced.

4.3.1. Statistical Analyses

The reduced data files contained, for each of ten subjects, a total of 914 observations (5 driving variables for each of 144 conditions, 3 attention variables for each of 40 conditions, 1 task variable for each of 32 conditions and 7 workload variables for each of 6 conditions). Summary data are contained in Appendix A, along with similar data from Experiments Two and Three.

The data were subjected to a variety of statistical analyses using the SAS Institute Inc. software. Throughout these analyses, a P=.01 level of significance was adopted to ensure the statistical reliability of effects.

Missing values were generated during the trial for Dwell time, when subjects did not look at the auxiliary display, and for task reaction time, when they did not perform the auxiliary task. Of course, both look frequency and viewing ratio were zero for conditions in which the subject did not view the auxiliary display. Observations for which missing Dwell time or auxiliary task performance values remained after data reduction were excluded from the appropriate analyses.

4.3.1.1. Effect of Task Load on Driving

To test for the effect of the presence/absence of an auxiliary task on driving, a 5 X 4 Repeated Measures ANOVA was performed (5 levels of treatment, TRT, consisting of 4 levels of task difficulty plus baseline, and 4 levels of curve type). Curve type was included in the analyses to test for interactions with task difficulty. In addition, hypotheses were tested contrasting baseline values and the means of the four levels of task difficulty. The results of the ANOVA are summarized in Table 2, showing the resultant F ratios. The asterisks indicate the F ratios which were statistically significant at the 0.01 level of confidence ($P<0.01$). The numerator and denominator degrees of freedom associated with each ratio is indicated in parentheses in the Source of Variation column beside the effect expression.

Table 2: Summary of 5 X 4 ANOVA

Source of Variation		TLC	EXC	SDLP	HDWY	VEL	SDVEL
TRT	F(4,36)	11.95*	3.09	8.75*	5.35*	0.74	3.92*
CRV	F(3,27)	42.63*	1.8	3.42	1.58	2.66	0.57
TRT*CRV	F(12,108)	1.89	1.1	1.15	0.77	1.45	1.44

The table indicates that several of the driving variables were affected by the treatment, i.e., the presence and nature of the auxiliary task. None of the interactions (TRT X CRV) was significant; hence, it was valid to examine contrasts between baseline and other treatment levels for the variables that had a main effect (e.g., time to line crossing, std. dev. of lane position, headway and std. dev. of velocity). The results of testing the contrasts between baseline levels and the mean of the four task difficulty levels indicate statistically significant ($P<.01$) differences for time to line crossing (F1,9=44.25), std. dev. of lane position (F1,9=21.85) and std. dev. of velocity (F1,9=13.78). Hence, it can be concluded that the presence of the auxiliary task affected the quality of driving observed.

Table 3 provides means and standard deviations for four driving variables under both single-task and dual task conditions. The dual task data were collapsed over the four levels of task difficulty. The relative magnitude of the performance decrements ranged from 14% (for time to line crossing) to 26% (for std. dev. of lane position).

Table 3: Effect of Auxiliary Task on Driving

	TLC		SDLP		SDVEL		HDWY (ns)	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Single-Task	3.5	0.76	0.19	0.05	0.75	0.28	54	9.2
Dual-Task	3.0	0.73	0.24	0.07	0.87	0.31	60	10.8

Figure 6 depicts these results in graphical form. It is clear that time to line crossing decreased while lane position variability and velocity variability increased as a result of the inclusion of the auxiliary task, suggesting a degradation in driving performance from levels observed under single task conditions. This trend was observed for the variable headway as well. Although for headway the contrast between baseline and the mean of 4 levels of task difficulty did not reach statistical significance (p<.03), it can be observed that headway increased from a baseline level of 54 metres to an average of 60 metres for the dual-task conditions. Headway was affected by the lag in dynamic response of the vehicle to accelerator control and, therefore, was less sensitive than other measures of driving. The increase in headway for dual-task conditions is consistent with observed degradations in the other performance measures in that the instructions to subjects specified that they were to maintain a headway of 50 metres.

Having established that the presence of the auxiliary task did adversely affect driving quality, the next question is whether the difficulty of the auxiliary task contributed in any way to this effect. In order to test for the effect of task difficulty, 4 X 4 ANOVA's were performed as in the previous analyses but excluding the single-task driving (baseline) condition. The results of these analyses are provided in Table 4, showing the resultant F ratios. The asterisks again indicate the F ratios which were statistically significant at the 0.01 level of confidence (P<0.01). The numerator and denominator degrees of freedom associated with each ratio is indicated in parentheses in the Source of Variation column beside the effect expression.

Figure 6: Dual Task Decrements in Driving Performance

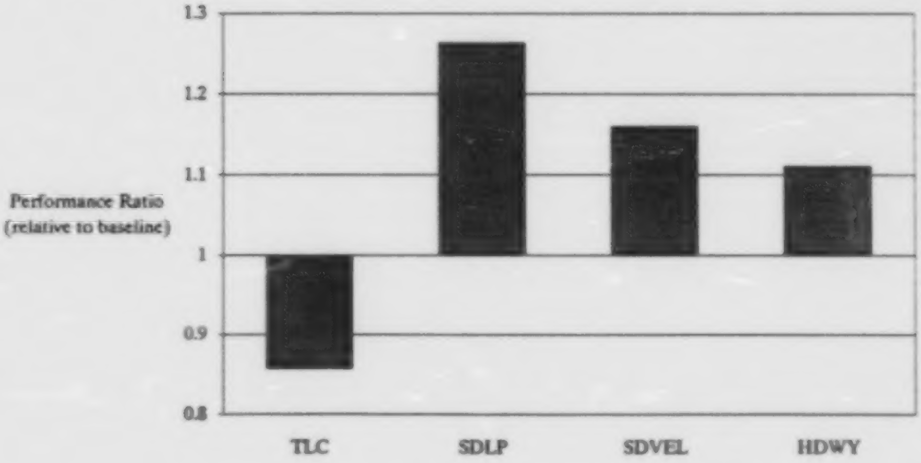
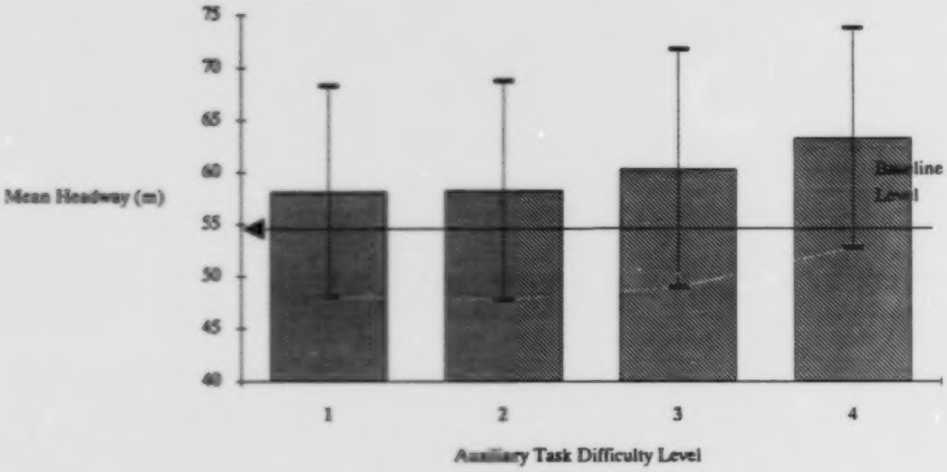


Table 4: Summary of 4 X 4 ANOVA of Driving Variables

Source of Variation		TLC	SDLP	HDWY	SDVEL
DIFF	F(3,27)	1.33	2.27	4.05*	2.06
CRV	F(3,27)	34.41*	1.72	1.09	0.52
DIFF*CRV	F(9,81)	1.01	1.15	0.96	1.41

This table indicates that headway was the only variable to have been affected by auxiliary task load as a main effect ($p<.01$). None of the interactions with curve type was significant. Figure 7 shows the relationship between headway and task difficulty. The standard error bars indicate that headway variability was high. The figure clearly shows that the main effect could be attributed to the observed increases in headway at difficulty levels 3 and 4. Evidently, the more difficult the auxiliary task, the greater was the average headway. This is interpreted as evidence for an adaptation mechanism by which subjects compensated for increased task load (implying increased visual and cognitive load) by increasing their reaction distance. It can also be observed in this diagram that, at all levels of task difficulty, headway under dual-task conditions was larger in magnitude than baseline levels. As indicated earlier, this signifies a degradation of car following performance under concurrent task conditions since subjects were instructed to maintain a constant 50-metre headway. Note that even under single-task driving, the headway levels were higher than the target level. It is interesting to note, that Colbourn et al. found that their subjects consistently adopted a headway of 2 seconds under a variety of driving conditions (Colbourn et al., 1978). The larger headways adopted by the present subjects may be due to cultural differences or to differences subjects may be due to cultural differences or to differences between closed-course driving and simulator driving.

Figure 7: Headway as a Function of Task Load



4.3.1.2. Effect of Driving Load on Driving Performance

Table 2 indicates that curve type had a significant main effect on time to line crossing. Figure 8 shows the relationship between time to line crossing and curve type. Auxiliary task difficulty levels and baseline levels are differentiated in the figure. It can be observed that time to line crossing, under all auxiliary task conditions, increased monotonically with radius of road curvature, establishing its sensitivity to driving demand. (Time to line crossing can be shown, in theory to be independent of road curvature, assuming a constant steering accuracy (Godthelp, 1984 page 84). Thus, an increase in time to line crossing with radius of curvature indicates reduced attentional demand, not more accurate steering.) Put another way, the more difficult the driving, the shorter the time margin for initiating corrective responses. It can also be readily observed, as was indicated in the previous section, that time to line crossing levels for all dual task conditions dropped significantly below corresponding baseline levels.

Finally, it can be observed that the magnitude of the time to line crossing (TLC) drop was also a function of road curvature. That is, higher road curvatures yielded larger decrements in TLC. The difference in slopes between baseline and dual task conditions provides further evidence for the phenomenon of driver adaptation. At relatively sharp curves (where TLC levels are low), dual-task TLC levels were relatively comparable to baseline levels; but at higher curve radii (where baseline TLC levels provided a good safety margin), the degree of intrusion by the auxiliary task was found to be greater.

4.3.1.3. Effects of Task Load on Attention

To test the effect of auxiliary task load and driving load on attention variables, 4 X 4 repeated-measures ANOVA's were performed, using 4 levels of curve type (CRV) (straight, 130-, 250- and 340-metre radii curves) and 4 levels of task difficulty (DIFF). The resultant F ratios are shown in Table 5. The asterisks indicate those F ratios which were statistically significant at the 0.01 level of confidence ($P<0.01$). The numerator and denominator degrees of freedom associated with each ratio is indicated in parentheses in the Source of Variation column beside the effect expression.

Figure 8: TLC as a Function of Road Curvature

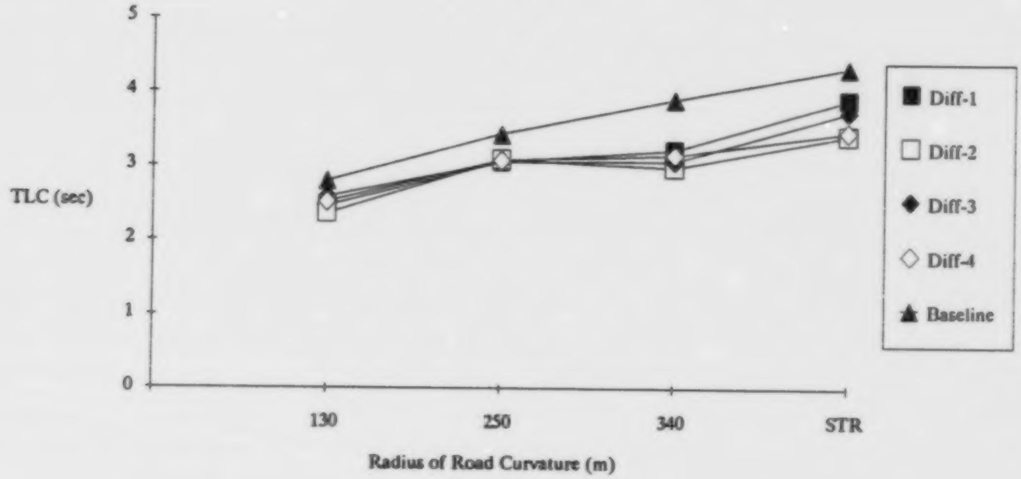


Table 5: Summary of 4 X 4 ANOVA of Attention Variables

Source of Variation		DWELL	VR	LFREQ
DIFF	F(3,27)	3.29 (24)	1.34	0.25
CRV	F(3,27)	5.29* (24)	50.85*	23.87*
DIFF*CRV	F(9,81)	1.10 (72)	3.04*	0.62

It should be noted that some data records contained missing values for Dwell time because subjects did not always look at the auxiliary display during all portions of the trial. Since repeated measures analyses cannot handle missing data, the data of only 9 subjects were used in the analysis of the dwell time data. The denominator degrees of freedom used in calculating the F ratios for Dwell time are shown in parentheses following the F value. Both look frequency and viewing ratio were zero for conditions in which the subject did not view the auxiliary display.

The data provide no evidence that auxiliary task difficulty affected any of the attentional variables. This statement must be qualified since a task difficulty X curve type interaction was observed for one of the variables, viewing ratio. The nature and interpretation of this interaction will be addressed later (under section 4.3.2.4) and shown not to detract from the overall lack of sensitivity of attention to auxiliary task difficulty (see Figure 12). That is, notwithstanding the presence of a second-order interaction for viewing ratio, attentional response does not appear to be affected by task difficulty, suggesting that attention is allocated primarily on the basis of driving load.

Figure 9 is a bar chart showing the effect of task difficulty on dwell time. An examination of this figure shows that mean dwell time increased with the difficulty of the auxiliary task, as might have been expected. However, because of the high variability in the data, as indicated by the relatively long standard error bars in the diagram, this effect did not reach criterion level of significance (P=.04).

4.3.1.4. Effects of Driving Load on Attention

It is clear from Table 5 that dwell time, viewing ratio and look frequency were all highly sensitive to road curvature. (Readers should recall that viewing ratio is equivalent to the product of looking frequency and dwell time.) Figures 10 and 11 show the dependence on Road Curvature of dwell time and look frequency, respectively. Examination of these figures indicates that both dwell time and look frequency increased sharply and monotonically with radius of road curvature. These results confirm the adaptation hypothesis that increased driving difficulty caused subjects to pay less attention to the auxiliary display. Of interest is the observation that look frequency more than doubled over the range of curvatures whereas dwell time increased by about 30%. This is consistent with information-theoretic predictions that look frequency is dependent on signal bandwidth (i.e., proportional to road curvature, Senders et al., 1964). These results are also in general accord with results of on-the-road studies which investigated the attentional demands of driving and found that eye movement behaviour (e.g., fixation durations, movement amplitudes and sampling frequencies) is dependent upon driving load (Ceder, 1977; Cohen, 1977; Senders et al., 1967; Shinar et al., 1977; Zwahlen, 1982). This fortuitous link with on-the-road studies lends validity to our results and confirms that subjects did indeed regard the driving task as the primary task.

Figure 9: Dwell Time as a Function of Task Load

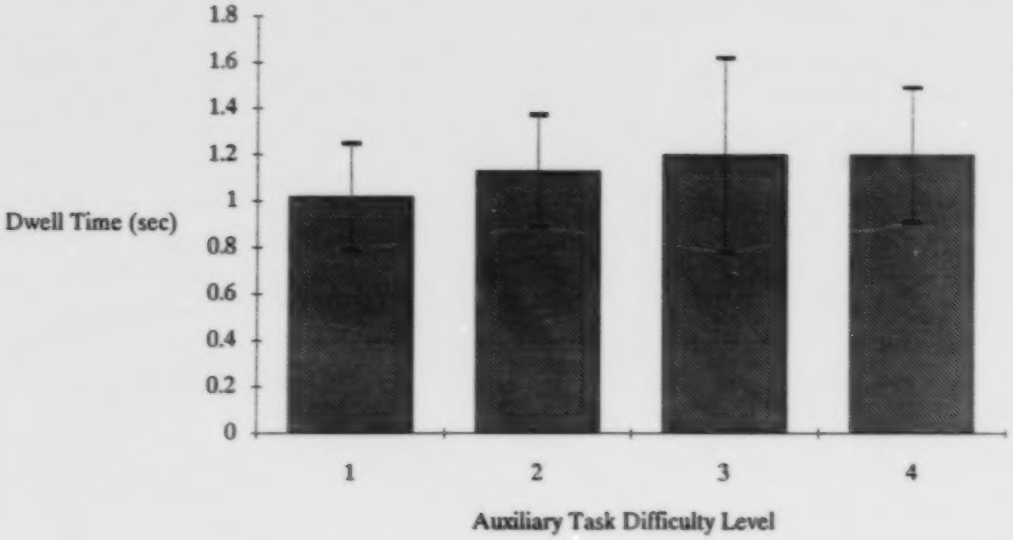


Figure 10: Dwell Time as a Function of Road Curvature

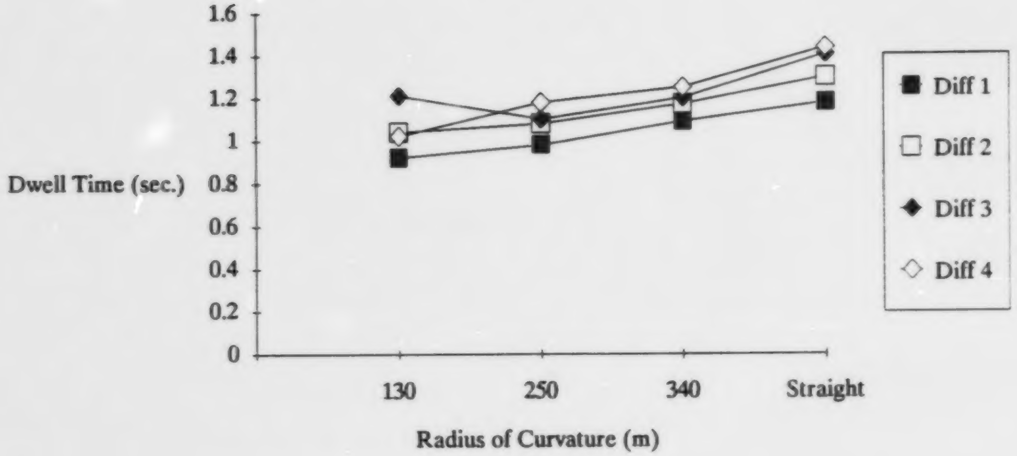


Figure 11: Look Frequency as a Function of Road Curvature

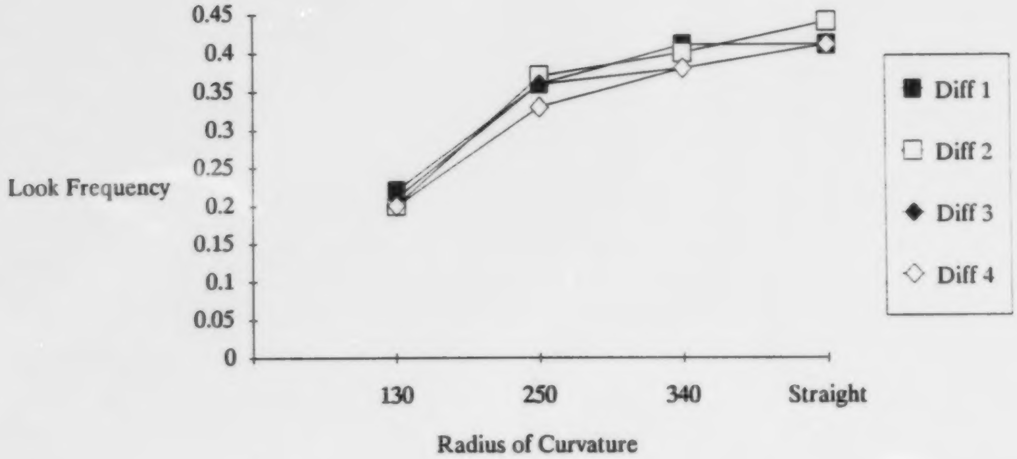


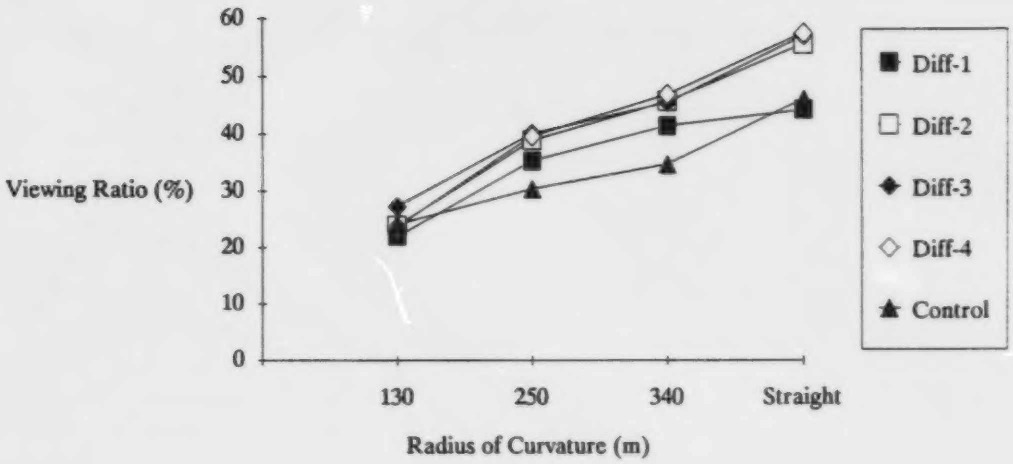
Figure 10 suggests that dwell time is also dependent to some extent on the characteristics of the auxiliary task, since the mean glance duration appears to vary systematically with auxiliary task difficulty - the more difficult the task, the longer the mean glance duration (though, this trend did not reach significance). This is consistent with the notion that fixation duration is proportional to the information content of the display (Senders et al., 1964). The look frequency data, on the other hand, did not vary in any systematic way with auxiliary task difficulty. It can be concluded, therefore, that the marginal increase in spare visual capacity associated with decreasing driving load was directed towards the auxiliary task primarily through increased sampling frequency. Glance duration also increased, though, proportionally, to a lesser extent.

Because both look frequency and dwell time increased as a function of decreasing driving load, a more robust measure of the amount of attention directed towards the auxiliary display was viewing ratio. Figure 12 plots viewing ratio as a function of radius of curvature. The four curves shown correspond to the four levels of task difficulty. The interaction between curve type and task difficulty that was noted earlier appears to be primarily due to the plateau in the data for difficulty level 1 which was in sharp contrast to the other curves (corresponding to other levels of task difficulty). Further ANOVA analyses confirmed that removing the level 1 data from the dataset eliminated the interaction effect. One possible explanation for this interaction is that, at this easiest level of task difficulty, subjects were able to achieve peak performance without committing additional resources to the task. That is, task performance was data limited at this level of task difficulty.

Notwithstanding the interaction between task difficulty and curve type, it is clear from Figure 12 that viewing ratio was highly sensitive to driving demand. Even for level 1 of task difficulty, there was a sharp increase in viewing ratio over the first three curves. The interaction, which was mostly due to one point, therefore, did not detract from the overall relationship between viewing ratio and road curvature.

It can be seen that viewing ratio increased from 20%, for high driving load conditions, to 50%, for relatively low driving load conditions - an overall increase of 150%. These results are in general agreement with the findings of McDonald and Ellis (1975). They employed the conventional secondary task paradigm to estimate attentional load on drivers driving over road segments of different radii of curvature and at different speeds. They reported that attention load, "percent occupied", was highly sensitive to road curvature and, to a lesser extent, speed and ranged from about 25% for 380-metre radius curves to about 45% for 100-metre radius curves (at speeds equivalent to 60 kph).

Figure 12: Viewing Ratio as a Function of Road Curvature



Finally, we can observe from the figure that, with the exception of the easiest version of the auxiliary task, there was no systematic effect due to task difficulty (the control condition will be discussed in a later section).

4.3.1.5. Effects of Driving and Task Load on Task Performance

The principal measure of auxiliary task performance was correct reaction time to negative displays (that is, the average latency for correct responses to displays having no targets). Because subjects were trained to attain a minimum of 95% response accuracy to minimize accuracy-speed tradeoffs, accuracy was not a meaningful measure of task performance. However, accuracy scores were obtained to verify that subjects did maintain the required level of response accuracy (95%). A negative logarithmic transformation was applied to the reaction time data to ensure homogeneity of variance. The negative transformation was used for plotting purposes to reverse the direction of the ordinate scale so that for a given point the quality of performance would correspond to its position relative to the positive direction along the ordinate axis.

A 4 X 4 ANOVA was performed on the transformed data to test for the effects of driving load and auxiliary task load on auxiliary task performance. The results of this analysis are shown in Table 6. It should be noted that some data records contained missing values for reaction time because subjects did not necessarily perform the auxiliary task during all portions of the trial. Since repeated measures analyses cannot accept missing data, the data of 4 subjects were used in these analyses.

The relationship between task performance and auxiliary task load is shown clearly in Figure 13, which is a plot of transformed reaction time values versus task load for single task and dual task conditions. This figure indicates that auxiliary task performance declined with increasing task difficulty. That is, the easier the task the better the performance, as would be expected.

Table 6: Summary of 4 X 4 ANOVA of Auxiliary Task Performance

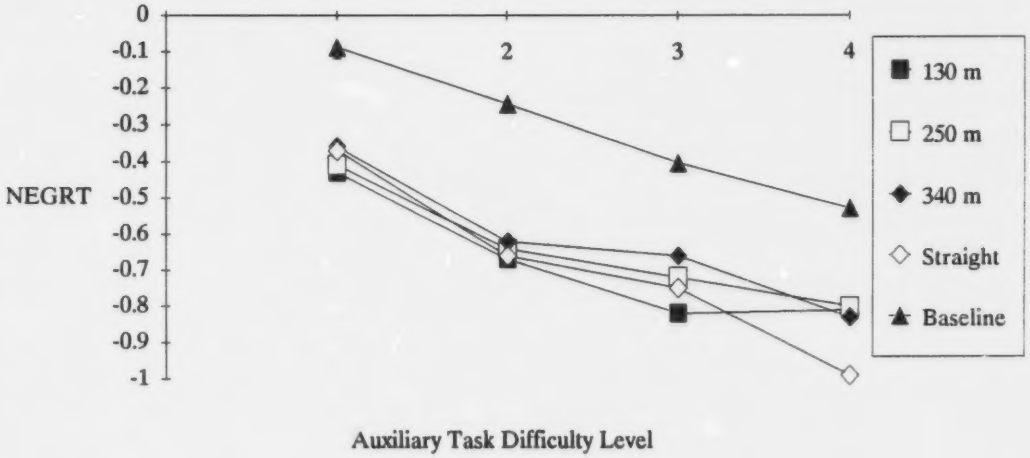
Source of Variation		NEGRT
DIFF	F(3,9)	31.49*
CRV	F(3,9)	4.77
DIFF*CRV	F(9,27)	1.87

Baseline data are plotted to demonstrate the degree of intrusion on auxiliary task performance that can be attributed to the primary task. Auxiliary task performance did not appear to be affected by the difficulty of the primary task.

4.3.1.6. Effects of Gaze Direction on Driving

One of the important features of the experimental setup was that it permitted the separation of performance data into two categories on the basis of where the subject was looking at the moment of sampling. This was possible because the Attention Monitoring System provided gaze direction information that was recorded together with the performance data. Hence, two levels of gaze direction were obtained; 'inside' and 'outside'. A third level, 'overall', represented the combined data for 'inside' and 'outside' conditions. However, for purposes of this section, the third level was omitted from the analyses, since our interest was in detecting differences between 'inside' and 'outside' conditions. It is important to recognize that gaze direction was not manipulated as an experimental variable; hence, the results can only be interpreted in terms of qualitative differences between these two conditions. That is, it would not be valid to draw inferences about cause-and-effect relationships from these results.

Figure 13: Reaction Time as a Function of Auxiliary Task Difficulty



Observations of subjects driving under concurrent task conditions during pilot tests confirmed that, while the subject was looking at the auxiliary display, he/she received minimal information from the roadway and, therefore, that he/she was driving in an open loop mode. It was hypothesized that driving performance during periods of inattention to the road would show measurable degradations relative to closed-loop driving.

Paired T-Tests were performed on the data to test for reliable 'inside'/'outside' differences. Differences (inside minus outside) were computed for each task difficulty and curve type combination for each subject. It should be noted that 'inside' and 'outside' exposures were not necessarily of comparable length (in sharp curves, for example, there were proportionately more 'inside' samples than 'outside' since subjects directed more visual attention towards the roadway), but such differences would not be expected to bias the comparison. Means and standard deviations of differences between inside and outside values are provided in Table 7 along with the t statistic for testing that the difference is zero, and the probability of a greater absolute value of t under the null hypothesis.

Table 7: Paired T-Test Results for 'Inside' and 'Outside' Looking Conditions

Variable	Mean Diff.	Std Dev	T	Prob > |T|
TLC	0.065	0.75	1.43	0.155
EXC	-0.012	0.04	-5.25	0.001 *
SDLP	-0.018	0.08	-3.80	0.001 *
HDWY	-0.282	13.12	-0.31	0.755
SDVEL	-0.085	0.28	-4.85	0.001 *

As stated earlier, because gaze direction was a dependent measure, rather than a variable that was experimentally manipulated, it is not valid to draw any cause-and-effect inferences from these results. However, the table indicates a strong relationship between gaze direction and driving quality as represented by lane exceedence ratio, lane position variability and velocity variability. Since headway changed relatively slowly over the trial, it was not responsive to changes in gaze direction. The paired T-Test for time to line crossing data also failed to distinguish more clearly between 'inside' and 'outside' looking conditions. It is postulated that the reason for this was that TLC was highly sensitive to curve type (much more so than the other driving variables) and that collapsing over curve type yielded relatively large variances which markedly reduced the statistical power of the test.

The values shown in Table 7 represent mean differences between the two levels of gaze direction ('inside' and 'outside'). It is important to note that driving variability (as indicated by std. dev. of lane position and std. dev. of velocity) as well as exceedence ratio were larger in magnitude while looking outside the vehicle than while looking inside. Similarly, although the time to line crossing data did not yield statistically significant differences, the positive sign is consistent with the trend exhibited by the other variables. These results are contrary to our original expectation that driving performance would be better under closed-loop conditions (with visual feedback) than under open-loop conditions. Instead the results indicate that driving quality was in fact worse when looking at the roadway than when looking at the auxiliary display.

The key to understanding these results is to realize that gaze direction was under the control of the subject, not the experimenter. Because gaze direction was not manipulated as an independent variable, it is not possible to test hypotheses concerning open-loop and closed-loop driving. The discrepancy between what was expected and what was observed, in our opinion, arises from the fact that the subjects, not the experimenter, decided when to look at the auxiliary display and when to look at the roadway. Since subjects were free to attend to whatever display they considered appropriate at that moment, their decisions about where to look were based largely upon their assessment of their performance at that instant and their confidence that the vehicle would remain within acceptable bounds of lane position and headway over the next second or so without their intervention. That is, drivers tended to look at the auxiliary display when they considered that it was relatively safe to do so (the vehicle was under control and they anticipated having to make no corrective action in succeeding time intervals). On the other hand, for most of the time that they were attending to the roadway subjects were actively involved in correcting vehicle lateral or longitudinal tracking errors. Under these conditions, driving quality would indeed be inferior when looking outside the vehicle than when looking inside.

These results lend further support to the notion of driver adaptability and provide some insight into the mechanism of selective attention. The results would suggest that a major factor underlying subjects' scanning strategy is their estimation of their driving performance. They adopted switching strategies that were designed to maintain driving quality within individually-set limits. However, notwithstanding subjects' ability to modulate looking behaviour to minimize auxiliary task intrusion, they were unable to completely prevent this from occurring (as indicated in previous sections).

Analysis was also performed to determine whether there were any reliable differences in the braking reaction time to truck deceleration (at the end of trial) as a function of whether the subjects was looking inside or outside during the onset of deceleration. Table 8 provides mean stop reaction times in seconds. The data indicate that it took about 3 seconds, on the average, for subjects to react to truck decelerations. Analysis of variance did not indicate that gaze direction had a significant effect. The failure to observe an effect may be due to the small number of braking events.

Table 8: Mean Stop Reaction Time

Treatment	Inside	Outside	Mean
Difficulty 1	3.03	3.31	3.17
Difficultv 2	2.95	2.82	2.88
Difficulty 3	2.76	2.93	2.84
Difficulty 4	3.17	2.97	3.07
Control	3.20	3.21	3.21
Baseline		2.84	

4.3.1.7. Effects of Task Load on Mental Workload

There were two main reasons for obtaining subjective workload assessments: a) to determine whether the subjects experienced greater workload under dual task conditions relative to single-task driving, and b) to determine whether subjective workload measures were sensitive to changes in auxiliary task load. Since subjective workload ratings were obtained at the completion of each trial, it was not possible to determine the sensitivity of workload measures to changes in driving demand (since all levels of curve type were presented during each trial). The workload ratings represented the subjects' assessment of workload for the specific level of task difficulty used in the trial integrated over all curves.

Analyses were performed for each of the individual component dimensions (scales) of workload in addition to the composite measure, the TLX index, in order to determine their relative sensitivities to dual task loading as implemented in the present experiment. Analyses of variance indicated that all workload ratings obtained under dual task conditions were consistently and reliably higher than corresponding ratings obtained under single-task driving ($p<.01$).

For each of the six individual workload metrics and the weighted composite, TLX, difference scores, calculated as the difference between dual task and baseline ratings, were determined for each subject. This procedure was used to compensate for individual differences in conceptualizing and formulating workload ratings. The resultant data were subjected to one-way ANOVA's in order to investigate the effect of auxiliary task load on subjective workload. The results are summarized in Table 9, which provides mean increases in workload ratings over baseline for each level of task difficulty as well as F ratios and the corresponding probability values.

Table 9: Mean Increase in Workload Ratings Over Baseline

	TLX	MD	TD	PD	E	P	F
Difficulty 1	8.2	7.8	14.5	6.3	5.0	5.8	14.5
Difficulty 2	12.1	14.3	19.0	10.5	6.8	8.0	15.5
Difficulty 3	13.1	13.3	19.0	11.0	6.8	6.8	19.8
Difficulty 4	13.5	16.8	19.0	11.3	11.0	6.3	16.3
F(3,27)	2.43	3.51	0.83	3.58	2.12	0.15	1.03
P	0.09	0.03	0.49	0.03	0.12	0.93	0.39

It is of interest to note that the composite index of workload, TLX, was less sensitive to auxiliary task loading than two of the component dimensions, Mental Demand (MD) and Physical Demand (PD). In fact, the effect of task load on TLX did not reach significance, while the effects on MD and PD were marginally significant. The fact that two of the workload dimensions exhibited sensitivity to increased task demands suggests that analysis of individual workload ratings can have some diagnostic value. Identification of the component dimensions most affected by the independent variable may provide valuable insight into how concurrent tasks combine to produce a loading response. For example, in the present experiment, the results suggest that cognitive and physical demands increased with auxiliary task difficulty. The reported increase in cognitive stress is hardly surprising, but the results also suggest that subjects experienced increased physical stress in performing the more difficult auxiliary tasks. This may be due, at least in part, to more frequent switching of attention for the more difficult tasks involving large head and eye movements. Interestingly, temporal demand (i.e., time stress) was not significantly affected by task difficulty.

The two dimensions found to be most sensitive in this study can be assumed to reflect the nature of the combination of the primary and auxiliary tasks. Had other tasks been used or the characteristics of the tasks (e.g., their relative location) changed, the results undoubtedly would have been different. This suggests that it would be prudent to analyze separately the various dimensions thought to underlie the experience of workload rather than to rely exclusively on a weighted composite measure. The diagnostic value of separate analyses cannot be over-stressed.

4.3.1.8. Serial versus Parallel Effects

As explained in an earlier section, there are two independent mechanisms that could give rise to the interference effects that were observed. One source of interference may be competition between parallel cognitive processes for common information processing resources. This might arise, for example, during open-loop periods when the subject is performing the auxiliary task whilst simultaneously controlling the vehicle (or during closed-loop driving whilst formulating and executing a response to the auxiliary task). This type of interference, arising from simultaneous demands of concurrent tasks, is referred to as parallel effects. Attention under such circumstances is said to be divided between the two tasks. The limitations underlying such effects are cognitive in nature.

A second source of interference is related to the physical inability of humans to visually fixate two separated displays simultaneously (or in close temporal proximity). That is, the physical act of turning one's head or moving one's eyes towards one object precludes (for the most part) processing information about a second object which may be present but not within the driver's foveal vision. This physical constraint produces time-sharing behaviour which is analogous to a selective filter. Attention under these circumstances is said to be serial (also sequential or focused), since the observer can only focus attention on one task at a time. Physical limitations are sufficient, but not necessary, to cause serial effects. It should be recognized that under dual task driving both cognitive and physical effects may be present.

It is therefore important to differentiate between the relative contributions of serial (physical) and parallel (cognitive) effects in producing interference. An understanding of the mechanisms underlying task interference within the context of driving will aid in the design and selection of appropriate driver interfaces.

To permit estimating the relative contribution of serial and parallel effects, a control condition was introduced in the experimental design. In this condition, the subjects' task was simply to look at the computer display as much as possible without allowing it to detract from their driving. Since the auxiliary display did not present a task for the subject to perform, the control task can be presumed to contain all of the physical elements of the auxiliary task but none of the cognitive elements. Two-way ANOVA's were carried out. One factor, treatment (TRT), comprised 5 levels; i.e., four levels of task difficulty plus the control task. The second factor was curve type. The results of these analyses are summarized in Table 10.

Table 10: Summary of 2-way ANOVA Comparing Parallel and Serial Effects

Source of Variation		TLC	EXC	SDLP	HDWY	SDVEL
TRT	F(4,36)	1.5	1.96	3.70*	2.16	2.43
CRV	F(3,27)	33.38*	2.74	3.62	1.45	0.35
TRT*CRV	F(12,108)	0.86	0.80	1.33	0.87	1.36

The table indicates the presence of a significant treatment main effect for std. dev. of lane position. For this variable, contrasts were generated between each level of treatment in turn against the control condition. With the exception of level 1 of task difficulty (the easiest level), the contrasts were all significant. Figure 14 is a plot of lane position variability as a function of curve type for each task condition. Baseline levels were also plotted for comparison. As can be seen from this figure, lane position variability for the control task was smaller in magnitude than corresponding values for most levels of the auxiliary task. These results would suggest that the auxiliary task produced larger variances in lane keeping performance than can be explained by serial effects alone. That is, it would appear that the cognitive components of the auxiliary task may have contributed to the degree of dual task interference that was observed.

Further support for this contention comes from examining a plot of TLC as a function of curve type. In Figure 15, time to line crossing data are shown for three conditions of driving - single task driving (baseline), driving while performing the control task and driving while performing the auxiliary task at a level 4 of task difficulty. Although the differences between the auxiliary task and the control task data did not reach statistical significance, the figure shows that the auxiliary task produced smaller TLC values than the control task, lending support to the claim that the cognitive elements of the task contributed to task interference.

Figure 14: Std. Dev. Lane Position as a Function of Road Curvature

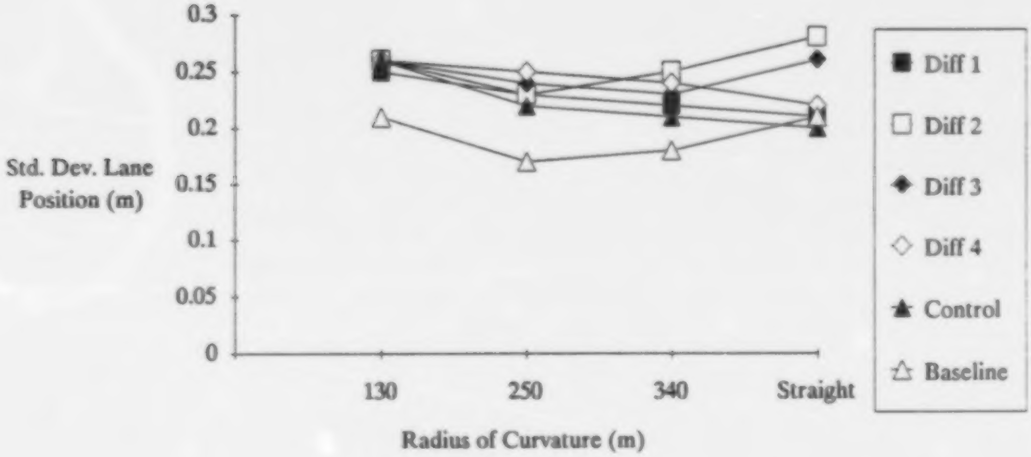
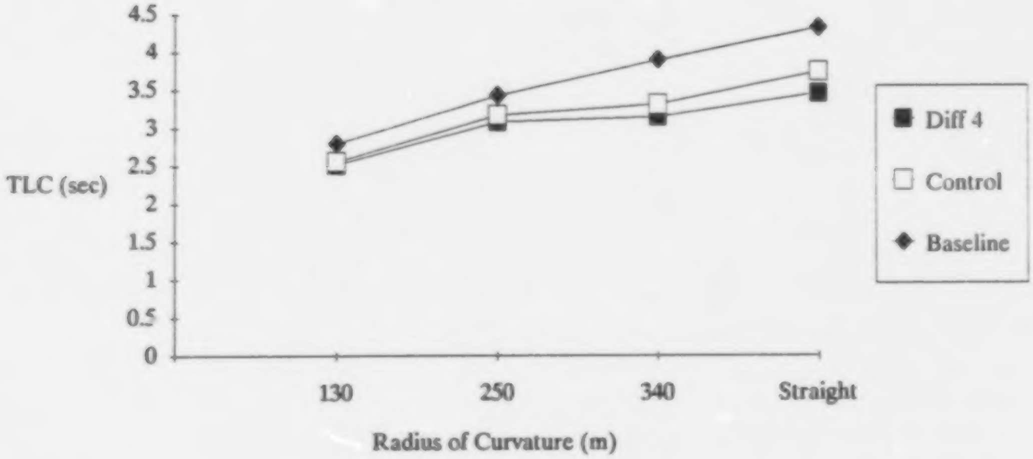


Figure 15: TLC as a Function of Road Curvature



This result would suggest that simply relocating the auxiliary tasks within the drivers' foveal vision (to eliminate physical competition) would not necessarily eliminate all sources of task interference since some degree of interference may be attributed to cognitive competition. Moreover, physical competition is not a necessary condition for serial processing; hence, even if two tasks are both presented within foveal vision, serial processing may still occur under certain circumstances.

An alternative explanation for the superior performance under the control condition is that subjects did not look at the auxiliary display as much when performing the control task as when performing the Perception task. This hypothesis, referred to as the attention hypothesis, is explored next.

Analyses of attention data yielded a significant treatment X curve type interaction for viewing ratio, $F(12,108)=2.78, p<.01$. Referring back to Figure 12, it was seen that a major element in this interaction was the levelling off of viewing ratio for the least difficult level of the auxiliary task for straight curves, in contrast to the other treatments which continued to produce monotonic increases in viewing ratio beyond the 340-metre curve. The explanation offered for this curious result is that performance for this simple task was data limited. More germane to the present discussion, however, is the observation that viewing ratio for the auxiliary task tended to be higher than viewing ratio for the control task. Simple main effects analyses confirmed that viewing ratio for the control task was significantly different from all task conditions for 250- and 340-metre curves and different from task difficulty levels 2, 3 and 4 for straight curves. This suggests that the auxiliary task commanded more attention than subjects were prepared to allocate to the viewing task. It lends support to the attention hypothesis for explaining performance differences between the control condition and the other dual task conditions. The confounding of attention and performance measures renders the evidence for the role of divided attention, albeit small, inconclusive.

Notwithstanding the possible small contribution of cognitive interference, the results of the present experiment clearly indicate that physical competition, not cognitive competition, was the major source of auxiliary task interference on driving. The requirement to periodically look away from the road to view the auxiliary display was the most disruptive element of the auxiliary task, not the task to be performed. Hence, the role of parallel processing under dual task driving was not relevant to auxiliary task intrusion on driving. This subject will be revisited under Section 5.3.4 of Experiment Two.

4.3.1.9. Effects of Field Dependence

Field dependence is a perceptual characteristic of an individual which describes the degree to which the individual can disembed relevant visual stimuli from the background (Witkin, et al., 1971). The most common instrument used for measuring field dependence is the Embedded Figures Test. This test measures the time taken to recognize a simple geometrical figure embedded in a complex figure. Attempts to determine the role of field dependence in accident causation and driving performance have been equivocal (Avolio et al., 1985, Lim and Dewar, 1988). However, the role of field dependence on drivers' attentional response had not been investigated.

In the present experiment, certain elements of the driving task required subjects to selectively attend to relevant stimuli in the road scene. Thus, the experiment provided an opportunity to investigate the role of field dependence on attentional response in a controlled driving experiment. It was hypothesized that field dependent subjects would fixate on the road display for relatively long periods compared with field independent subjects.

Subjects were divided into two equal size groups on the basis of their EFT scores. The median score was 43; hence, subjects were classified as field dependent (or field independent) if they attained a score higher (or lower) than 43. Table 11 provides a listing of subjects in each group and their EFT scores.

To test the relationship between field dependence and measures of driving performance and attention, a series of 3-way repeated measures ANOVA's was performed on the data using 2 levels of field dependence (TYPE), 4 levels of task difficulty (Difficulty) and 4 levels of curve type (CRV). Analyses were also performed for performance variables to test whether field dependent subjects performed less well than field independent subjects. The results of these analyses are summarized in Table 12, showing the resultant F ratios. The asterisks indicate that the F ratio was statistically significant at the 0.01 level of confidence ($P<0.01$). The numerator and denominator degrees of freedom associated with each ratio is indicated in parentheses in the Source of Variation column beside the effect expression.

Table 12 does not provide evidence that field dependence affected either attentional behaviour or performance. Specifically, field-dependent subjects did not look at the roadway any more than their field-independent counterparts as was expected if they experienced more difficulty in visually distinguishing relevant objects from background elements. However, it should be pointed out that the lead truck and the road elements used in the primary display were easily discernable from the buildings and other background elements and, therefore, field dependence might not have played as large a role under present experimental conditions as it might have had the display been visually more complex. An alternative explanation is that, with 5 subjects per group, there were insufficient data to properly test for the effects of field dependence.

Table 11: Field (In)dependent Group Membership

FIELD DEPENDENT		FIELD INDEPENDENT	
ID	EFT	ID	EFT
FG	47	AF	18
KP	48	CH	24
HK	46	TH	20
JP	55	TS	32
GS	91	JK	42

Table 12: Summary of 3-way ANOVA Testing Effects of Field Dependence

Source of Variation		VR	DWELL	LFREQ	TLC	HDWY	SDVEL
TYPE	F(1,8)	0.39	1.16	0.03	0.0	0.51	5.35
CRV	F(3,24)	53.6*	26.09*	24.58*	32.98*	1.32	0.52
CRV*TYPE	F(3,24)	1.49	0.56	1.27	0.62	2.89	0.96
Difficulty	F(3,24)	1.44	3.22	0.26	1.73	3.99*	1.99
Difficulty*TYPE	F(3,24)	1.68	1.31	1.36	3.72	0.87	0.72
CRV*Difficulty	F(9,72)	3.06*	0.85	0.62	1.01	0.91	1.43
C*D*TYPE	F(9,72)	0.40	1.01	1.00	1.00	0.55	1.13

4.4. DISCUSSION

4.4.1. Methodology Evaluation

The results of this experiment confirm the validity of the present methodology for investigating drivers' primary task performance and attentional response under dual task conditions. The dependent measures that were employed were found to be sensitive to differences between single and dual task conditions as well as to manipulations of driving difficulty and auxiliary task difficulty. Driving task difficulty was found to have a larger effect on driving performance and attention than auxiliary task difficulty. These results are in agreement with results of studies which have investigated the relationship between eye movement behaviour and driving demands under single task conditions.

Primary task measures of time to line crossing and headway were found to be the most reliable and sensitive to changes in both primary and auxiliary task loading in a car following task. These two measures also possess a high degree of construct validity in that they relate most closely to the visual cues required for lane keeping and car following. For a more detailed discussion of the role of TLC as a perception-decision factor in vehicle control, the reader should consult papers by Godthelp.

Visual scanning behaviour was also found to be sensitive to manipulations of driving and auxiliary task difficulty. The composite attentional measure, viewing ratio (representing the percent time looking at the auxiliary display), exhibited a significant and large dependency on the difficulty of the driving task. The other variables of attentional response exhibited similar trends. Dwell time also appeared to exhibit a dependency on the difficulty of the auxiliary task, though this effect did not reach criterion level of significance.

Interestingly, the intermediate attentional variables were more sensitive to experimental manipulations than the primary driving variables. One possible explanation for this is that subjects were able to maintain primary task performance within desired bounds by judiciously modulating their scanning behaviour in response to changing task requirements. Hence, attentional response fluctuated far more so than did the primary task measures. Another possible explanation for this is that increased dual-task demands resulted in increased workload, but that the workload levels attained were within the subjects' capacity and, therefore, had little effect on performance. It is widely recognized that primary task performance is not a particularly good indicator of cognitive load or of time-sharing demands. Attention variables, on the other hand, would be expected to be more sensitive to changes in dual-task demand.

4.4.2. Mutual Intrusion and Inferences

The results from the present experiment provide evidence that degradations in driving performance can occur when using auxiliary displays. In particular, time to line crossing, std. dev. of lane position, headway, and std. dev. of velocity were significantly affected by the presence of an auxiliary task. The increased variance of speed is particularly important to traffic safety, since these measures have been shown to correlate with accident experience. In a recent analysis of traffic data and accident statistics at 36 sites in the State of Virginia, Garber and Gadirau (1988) found that accident rates increased dramatically with speed variance. Their regression models based on speed variance alone accounted for 60% of the variance in accident rate for interstate highways and 82% of the variance for arterial highways. The variable, headway, was also found to be sensitive to difficulty manipulations of the auxiliary task. The tendency for headway to increase with increasing task demand is consistent with findings reported elsewhere. For example, Rockwell (1972) investigated the effects of traffic density on headway and found that headway increased with primary task difficulty.

Analyses of attentional data confirmed that a significant portion of the drivers' attention was directed away from the roadway under dual task conditions, and dwell time increased somewhat as the auxiliary task became more difficult. As indicated earlier, the effect on attentional response was in fact far more pronounced than the effect on primary task measures. In many respects, however, attentional response is a more useful indicator of task intrusion than driving performance because the former reflects more accurately the drivers' perceptions of road performance requirements and experiences of workload. In this respect, attentional response can serve as an early indication that workload demands are approaching critical levels. Furthermore, even under sub-critical conditions, the consequences of misdirected attention (away from the roadway) during occurrences of sudden or unexpected events in the road environment (such as an unexpected change in road surface, intrusion of an object or pedestrian in the traffic, etc.) could well lead to increased risk of collision due to delayed response or a lack of response on the part of drivers (Sussman et al., 1985). In the present experiment, the effect of inattention on the latency of response to unexpected events was difficult to assess. (Although an attempt was made to estimate this by triggering lead truck decelerations on the basis of whether subjects looked inside or outside the vehicle, there were insufficient data to investigate the effects of gaze direction on brake response latency.)

The fact that attentional response fluctuated so greatly in the present experiment indicates that auxiliary tasks can have potentially more serious implications for traffic safety than might otherwise be indicated by primary task performance alone. Moreover, while the absolute magnitude of the effect on driving might have been relatively small, it should be recognized that a slight increase in driver error probability (due to misdirected attention), though barely detectable in experimental data, may have dramatic impact on national road safety statistics because of the magnitude of driving exposure (126 billion kilometres per year in Canada for passenger cars alone). For this reason, in analyzing the data, emphasis was placed on reliability of effect rather than its magnitude (i.e., a 0.01 level of confidence was used).

The results indicate that the primary source of interference was physical rather than cognitive in nature (i.e., subjects could only look at one display at any given moment). However, the results also suggest a possible role for cognitive interference.

4.4.3. Evidence for Driver Adaptation

The data provided compelling evidence (converging from a number of separate analyses) for the presence of driver adaptation - the ability of drivers to alter their behaviour to compensate for changes in the perceptual, mediational, and motor demands imposed by competing tasks in an effort to achieve an acceptable level of driving performance. An example of this phenomenon was the observed increases in headway under increasing dual task loading which was interpreted as compensating for increased workload. Also, the relationship between TLC and road curvatures provided evidence for reduced tracking effort due to decreased driving load. Similarly, viewing ratio was found to increase sharply with increasing radius of curvature signifying increased attention to the auxiliary task with decreased driving demand.

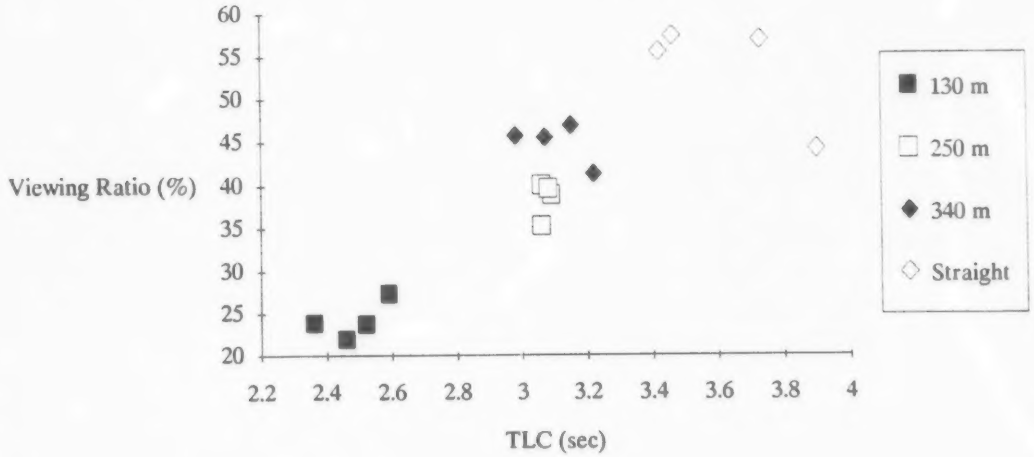
Perhaps the most compelling evidence comes from the comparison of driving performance while looking outside the vehicle with performance while looking inside. The results were contrary to initial expectations, but, upon reflection, were found to be consistent with the notion of driver adaptation. It was suggested that driving performance was better while looking inside the vehicle because this condition was most likely to be observed when the vehicle was under control and its projected path over the next few moments was judged to permit safe scanning of the auxiliary display. The discrepant result was, therefore, due to lack of validity in the original hypothesis - the subject, not the experimenter, decided when he/she would attend to the auxiliary display. Hence, the data cannot be interpreted in terms of closed-loop or open-loop performance; rather they suggest that subjects' allocation of attention was modulated by their momentary assessment of driving demand.

To illustrate the presence of driver adaptation, we have plotted the relationship between attention variables and driving performance. Figure 16 is a cluster diagram showing viewing ratio against TLC for data representing task difficulty and curve type condition combinations. Clearly, there is a strong association between these two variables. The apparent clustering of data into groups having common road curvature and the systematic ordering of these clusters is even more striking. At high road curvatures (high driving demand) both TLC and viewing ratio are relatively low. As the radius of curvature increases (moving from one cluster to the next) both measures increase proportionally. Average linkage cluster analysis was performed to test whether resulting clusters corresponded to levels of road curvatures. The results indicated close correspondence. As can be seen in this figure, within each cluster, the effect of task difficulty was not systematic.

As stated earlier, because TLC and viewing ratio were both dependent measures, any systematic trend in the data cannot be used to infer cause-effect mechanisms. Nonetheless they serve to highlight the association between these variables and provide further insight into the selective attention process. Attention variables can be considered 'intermediate' in the sense that they reflect the subjects' assessment of both driving load and auxiliary task load and decision about relative priorities. Attention variables are also intermediate in the sense that they intervene between road performance requirements and actual driving performance, as illustrated in Figure 1.

A similar result was obtained for the relationship between the transformed reaction time data and headway. Here, the best clusters correspond to levels of task difficulty, though some overlap was apparent in this scheme. As dual task load increased (due to increasing difficulty of the auxiliary task), both headway and reaction time increased. This is consistent with the notion of driver adaptation assuming that increases in headway were caused by drivers falling back to compensate for reduced attention to the lead truck.

Figure 16: Viewing ratio Versus TLC



5. EXPERIMENT TWO

5.1. PURPOSE

The results of Experiment One demonstrated the existence of mutual interference when driving in a simulator was shared with an auxiliary task presented on a dash-mounted computer display. Primary and auxiliary task difficulty were found to affect attentional response and, to a lesser extent, driving performance. Despite the presence of driver adaptation, the results indicated that auxiliary displays can adversely affect driving quality. Attentional response was considered to be a more sensitive indicator of driver workload than primary task measures and proved to be a valid metric for assessing the potential impact of auxiliary displays on driving.

However, the results of Experiment One do not necessarily generalize to auxiliary tasks which possess different properties than the Perception task that was used in the experiment. In other words, the degree of intrusion that was observed in the first experiment may well be specific to the particular combination of the auxiliary and the primary tasks that were employed. The question addressed in this second experiment, therefore, was whether other auxiliary tasks (that differ in some fundamental way from the Perception task) produce different patterns of attentional behaviours and intrusion on driving or whether the results of the first experiment are independent of task type.

A review of the current literature was conducted in attempting to identify the critical dimensions of displayed tasks that are likely to affect their joint performance. A number of different theoretic schema have been identified for classifying auxiliary tasks in terms of their relationship to a given primary task in a task sharing situation (Wickens, 1984). The most relevant are based on principles that have attempted to explain dual-task interactions, including (a) intra-task competition for information processing resources, (b) secondary task stimulus-central processing-response (S-C-R) compatibility, and, (c) task integrality (Tsang et al., 1986).

The S-C-R compatibility principle is widely accepted (i.e., S-C-R compatibility enhances performance and minimizes likelihood of interference with other tasks), though the costs (or disbenefits) of incompatibility are not always readily quantifiable. It is reasonable to expect that designers of auxiliary tasks will naturally strive for maximum S-C-R compatibility. However, the costs of achieving S-C-R compatibility may not always appear to be justified. To aid designers make appropriate decisions, it would be useful to quantify the effects of S-C-R compatibility on task performance and interference. However, the present study was designed to identify and assess the most relevant task dimensions; hence, it was sufficient to recognize S-C-R compatibility as an important factor. Further study of this principle was not warranted due to widespread acceptance of its importance. The third principle, task integrality, has special application in situations in which the primary and auxiliary tasks possess certain common properties or relationships. Task integrality might have relevance, for example, for HUD's displaying lane tracking errors. However, this principle was not considered of general relevance to most auxiliary displays.

Perhaps the principle most relevant to automotive applications concerns intra-task competition for information processing resources, as described by multiple resource theory (Wickens, 1980). According to multiple resource theory, resources can be thought of as independent structures dedicated to performing very specialized processing functions. Multiple resource theory proposes that processing resources can be discriminated along three dichotomous dimensions: stages of processing (encoding and central processing vs. response); codes of perceptual and central processing (verbal vs. spatial); and modalities of input (visual vs. auditory) and responses (manual vs. vocal). The theory suggests that the degree of mutual interference that occurs between time-shared tasks depends upon the extent to which concurrent tasks compete for common processing resources. Multiple resource notions, therefore, can have important implications for specifying the characteristics of auxiliary displays. While multiple resource theory does not define resource space in great detail (e.g., identify the functions of specific resources) nor quantify the relationship between the degree of competition for specific resources and the expected level of mutual interference (which would be useful for tradeoff analyses), the concept of resource competition is sufficiently well formulated that its relevance to automotive display ergonomics is testable. Hence, a need was identified to assess the role of auxiliary task resource structure (as perhaps the most critical auxiliary task dimension) on selective attention and performance under dual-task driving.

Experiment Two was therefore designed to determine whether task resource structure affects drivers' attentional response and performance under dual task conditions and whether multiple resource theory predictions hold under dual task driving applications. The Perception task employed in Experiment One involved visual, spatial and perceptual resources; hence, it presented a potentially high degree of resource competition with driving. Multiple resource theory proponents would contend that it should be possible to lessen the impact on driving performance by judiciously specifying the characteristics of the auxiliary task, such as input modality, so as to reduce the expected degree of competition with the driving task. The specific objective of this experiment was to examine whether such improvements can indeed be achieved. To do this, a second task, a verbal memory task, was devised which had fewer resources in common with driving.

The verbal memory task differed from the Perception task along two principal dimensions - stages of processing (perception vs. cognitive memory) and codes of perceptual and central processing (verbal vs. spatial). It should be noted that, while the formal theory may not differentiate between perception and memory resources, this differentiation is implicit in much research by multiple resource theorists (Wickens et al., 1983). The verbal and memory elements of the Memory task were specifically selected so as to minimize competition for processing resources that are presumed to be required for driving. Goettl (1985) provides evidence for code-specific interference (i.e., greater interference was observed when a memory and a cognitive tasks of the same code were combined than when they were of different code). Hence, whereas resource competition between the Perception task and driving was high, the resource competition between the Memory task and driving was low. On the basis of multiple resource theory, it was predicted that the Memory task would interfere to a lesser extent with the driving task than the Perception task of Experiment One.

It should be noted that both the Perception task and the Memory task involved visual input modalities and manual response modalities and that these resources were also invoked by the driving task. While it was possible to select input and response modalities for the Memory task that would have ensured greater separation between resources of the primary and auxiliary tasks, to do so would have introduced unnecessary complications. For example, it was possible to devise an auditory version of the Sternberg task to further reduce resource competition; however, this would have necessitated a change from subject-paced presentation of the task to experimenter-paced presentations. Such a fundamental change in the nature of the task was undesirable, since the emphasis of the study was on voluntary driver response to auxiliary displays. Moreover, since the primary interest of this study is the intrusive effects of visual displays, it was necessary to limit the scope within manageable theoretical, methodological and statistical bounds. The use of an auditory Sternberg task would have made it nearly impossible to determine the focus of the subject's attention, since attention allocation could no longer be inferred from simple eye movements. It should be recognized, however, that the results are not generalizable beyond visual tasks. However, within this limitation, there was sufficient scope for testing multiple resource theory predictions.

5.2. METHODOLOGY

5.2.1. Experimental Design

Attention and performance data were obtained for the Memory task group using the dual-task protocol that was employed in Experiment One. These new data were reduced and combined with the data of Experiment One to yield a 3-way mixed factorial design. As in Experiment One, the within-subjects factors were auxiliary task difficulty and driving difficulty. The between-subjects factor was task type, having 2 levels corresponding to the two auxiliary tasks - Perception task and Memory task. Since the primary purpose of this experiment was to test for the effects of resource structure, it was less important to compare the two tasks directly than to determine whether the differences between tasks led to differential effects of task difficulty and curve type. The mixed design was appropriate, since it gave most power to statistical tests of the effects of interest - interactions between task type and the within-subject factors.

5.2.2. Experimental Protocol

The experimental apparatus and set-up are described in Experiment One. The test protocol, however, employed a verbal memory task (as described under separate heading) in place of the Perception task. The data thus collected were combined with those collected in Experiment One for statistical analysis; hence, Experiment Two was in fact an expansion of Experiment One. This section of the methodology, however, describes the procedures employed for collecting the new data (i.e., data for the group of subjects given the Memory task).

As in Experiment One, a 4 X 4 factorial repeated-measures design was used in which primary and auxiliary task difficulties were manipulated. The four levels of primary task difficulty presented corresponded to different levels of road curvature, as described previously. The four levels of auxiliary task difficulty corresponded to memory sets of different size, as described under a separate heading dealing with the 'Memory Task'.

In addition, two control conditions were employed. The cognitive control condition permitted estimating the relative contribution of physical interference (as opposed to cognitive interference) arising from the need to move one's head and/or eyes to view the auxiliary display. In this condition, the subject was asked simply to look at the display as much as possible without allowing the task to affect driving performance. As no responses were required for this condition, no perceptual or cognitive load was present. In order to motivate subjects to look at the display, the accumulated viewing time was displayed in the middle of the screen.

The second control condition was single-task driving. The baseline data were obtained during pre- and post-experimental trials in which subjects were required to perform the driving task alone to the best of their abilities. That is, no auxiliary task was presented during these trials and subjects were instructed to drive the course giving their complete attention to the forward display.

Single task baselines were also collected for auxiliary task performance. During these trials, vehicle motion was produced through automatic drive programs to control for any possible effect that motion may have on auxiliary task performance. Hence, the kinesthetic and peripheral visual cues were present without any of the overt demands associated with the driving task.

For a detailed description of the experimental set-up and apparatus, the reader is referred to the appropriate sections of Experiment One.

5.2.3. Memory Task

The auxiliary task was a modified Sternberg memory search task (Sternberg, 1969). The Sternberg task was well suited for this study because it involved verbal/memory resources and as a consequence it differed substantially from the Perception task along two of the three multiple resource dimensions. The Sternberg task requires subjects to first memorize a set of alphabetic characters which are referred to as the memory set. The memory set size is often manipulated to vary the difficulty of the task (typically 1-5 characters are used). A set of probe characters is then presented in sequential order and the subject is instructed to indicate, for each, whether the displayed character was or was not contained in the memory set. Measures of reaction time to positive (i.e., probe is a member of the memory set) and negative (i.e., probe is not a member of the memory set) displays are obtained. For a review of the rationale and diagnostic value of the Sternberg task in secondary task paradigms, the reader is referred to Wickens et al. (1986).

Unlike the conventional Sternberg paradigm, however, the present task employed three simultaneous probes instead of a single probe for reasons explained later in this section.

The Memory task was adapted to the present experiment in such a way that test procedures were essentially identical with the procedures used for the Perception task - only the cognitive aspects of the two tasks differed. Before the start of each trial, subjects were presented a set of characters (ranging in size from 2 to 5) to memorize. During the trial, randomly selected characters (probes) appeared three at a time in the display and subjects were required to indicate whether any of the three probes matched any of the letters in the memory set that was presented to them at the beginning of the trial. Due to the possibility of confusion (acoustic and visual), the letters D, K, M, N, P, T, U, V, and W were not used. Memory set items were randomly selected from the remaining 17 characters. Task difficulty was manipulated by varying the number of letters in the memory set. Four levels of task difficulty corresponded to memory set sizes of 2, 3, 4, and 5 letters. Many previous studies employed set sizes as large as six or more items (Eriksen et al., 1986), though Wickens et al. (1986) recommend not employing sets much larger than four.

A memory set of one was avoided as evidence has shown (Wickens et al., 1986) that there is essentially no scanning of memory under this special condition.

Positive and negative displays (presence and absence of a target) were presented with equal probability. Subjects responded by depressing the right and left foot switches for positive or negative displays respectively. Subjects were trained to keep the error rate below 5% when performing the auxiliary task. This eliminated the possibility of speed-accuracy tradeoff effects. Error rate feedback was provided at the completion of each trial and subjects were encouraged to maintain a high accuracy score.

The auxiliary task was self-paced; that is, each response triggered a new presentation. In this way, the subject was completely free to direct attention to either display as circumstances required.

As mentioned above, the Memory task employed three probes rather than the conventional one. This was done in an attempt to match the difficulty levels of the Memory task to the difficulty levels of the Perception task. In preliminary tests of the Memory task using one probe, reaction time for a memory set size of 2 characters was observed to be of the order of 1 seconds. For a memory set size of 5 characters, reaction time increased only slightly to 1.3 seconds. In order to achieve baseline reaction time levels more comparable with the corresponding difficulty levels of the Perception task, it was necessary to make the Memory task more difficult without increasing memory set sizes - set sizes greater than 5 are not recommended (Wickens et al., 1986). One way of achieving this was to increase the number of probes simultaneously displayed on the screen. This approach to increasing task difficulty has an important additional benefit - it forced subjects to visually scan the auxiliary display to acquire the test stimuli, a requirement that was also imposed by the Perception task.

A preliminary study was run to determine the number of probes which produced the closest match (in terms of reaction time profiles) to the Perception task. In the pilot study, the number of probes was varied between 1 and 3 and memory set size was varied from 2 to 5. The results indicated that the use of 3 probes produced reaction time profiles (i.e., reaction time vs. difficulty curves) which were comparable to the Perception task. On the basis of these results, the 3-probe version of the Memory task was selected.

It should be noted that post experimental comparisons of baseline reaction time data, shown in Figure 17, confirmed that both the Perception task and the Memory task produced similar reaction time profiles, though the Perception task exhibited somewhat higher sensitivity to auxiliary task difficulty.

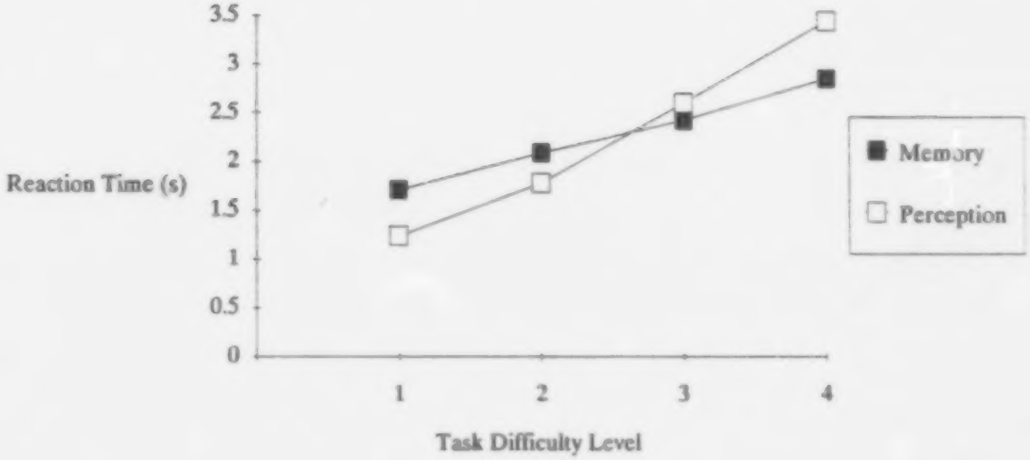
The Memory task was easy to learn and performance on the task asymptoted rapidly. Although learning was essentially complete by the third trial, subjects were given at least five trials of single-task practice to learn this task.

5.2.4. Dependent Measures

Measures of driving performance, attentional behaviour and auxiliary task performance were obtained throughout the trial at a sampling rate of 20 Hz. In addition, the NASA multidimensional Task Load Index (TLX) technique was used to obtain subjective mental workload ratings at the end of each trial in an effort to determine subjects' response to increased demands under dual-task conditions.

The Attention Monitoring System indicated which display, the forward visual scene or the auxiliary display, was being fixated during each sample interval. Hence, in addition to run averages for the various measures, it was possible to compute separate statistics for 'inside' (driver looking at the auxiliary display) and 'outside' (driver looking at the forward display) looking conditions.

Figure 17: Auxiliary Task Normative Data



5.2.5. subjects

Subjects were ten new student volunteers - five males and five females. None of these subjects had participated in previous experiments at UTIAS. Two of the subjects withdrew from the experiment due to simulator sickness and they were replaced. Subjects ranged in age from 19-37 years, with a mean age of 24.9 years. All of them had normal vision. All of the subjects had a minimum of three years of driving experience and all owned their own vehicle. Candidates with poor driving records or who had been involved in traffic accidents during the previous three years were eliminated from the study. Subjects were paid $100 for their participation in the study.

Perceptual and cognitive tests were administered to successful candidates in an attempt to determine the potential role of cognitive and perceptual style in producing individual differences. These tests included the Embedded Figures Test for field dependence/independence (Witkin et al., 1971) and the Contrast Sensitivity vision test, using Visitech's Vision Contrast Test System.

Each subject was requested to sign a consent form indicating that he/she understood the nature of their participation in the experiment.

Each subject received nearly four hours of single and dual task training a day or two prior to testing to ensure good familiarity with the equipment and the experimental procedures. The training procedures are described in more detail under Experiment One. The training sequence began with a series of single-task driving trials followed by a series of auxiliary task trials and concluded with a series of dual-task driving trials. During the auxiliary task training, each subject was trained to achieve a minimum accuracy level of 95% (this level of accuracy was imposed to preclude potential speed/accuracy tradeoff effects). The subject's acquisition data were plotted during each phase of training to ensure that his/her performance had asymptoted before proceeding to the next phase of training. Prior to the dual-task trials, the subject was reminded that driving was to be regarded as the primary task and only to perform the auxiliary task when it was considered safe to do so.

5.2.6. Procedures

The subject arrived in the laboratory fully trained in the experimental procedures. The EOG electrodes were attached to the outer canthus of each eye and behind the left ear. The eye tracker was calibrated according standard procedures to ensure good signal response. The subject was then directed to the simulator. The seat was adjusted to the subject's comfort. The head band containing the head tracker transmitter was placed on the subject's head and the head tracking system was calibrated.

The subject was then given two complete dual-task driving trials for practice. During these trials, the auxiliary task was set at an intermediate level of difficulty (i.e., a memory set size of 3 was used).

The formal part of the experiment was divided into two sessions separated by a 30 minute rest break. Each session lasted about two hours. The first session comprised 8 trials, whereas the second session comprised 7 trials, for a total of 15 trials. Fifteen of the roads from the roads library were randomly assigned to the 15 trials.

The first and last trial were reserved for collecting pre- and post-experimental baseline data. The pre-experimental trial consisted of 4 consecutive one-minute blocks in which subjects performed the auxiliary task alone. The four blocks corresponded to four levels of task difficulty. At the completion of the single-task auxiliary task blocks, the subject was asked to drive a complete course in which no auxiliary task was presented. The post-experimental trial followed the same protocol but this time the four auxiliary task blocks followed the driving trial.

Three of the 15 trials were designated as 'throwaway' trials. These trials had very short durations and were included as a means to prevent subjects from forming trial duration expectations. The throwaway trials always occurred as trials 2, 5 and 8 and ran for 1, 1.5 and 2 minutes respectively. No data were collected during these trials.

Ten dual-task driving conditions were randomly assigned to trials 3, 4, 6, 7, 9, 10, 11, 12, 13 and 14. There were two replications each of 4 levels of task difficulty (yielding eight trials) and the control condition (yielding two trials). The order of these ten trials was counterbalanced across the ten subjects according to a Latin Square design. The experimental trials ran 4 to 6 minutes each. Curve type (or driving difficulty) varied within trials according to the curvature profile of the road assigned to the particular trial.

5.3. RESULTS

Summary data are contained in Appendix A. The data were combined with the data of Experiment One for statistical analyses. The resultant database conformed to a mixed design (within-between) that was especially well suited for investigating the main effects of driving and auxiliary task difficulty (the within-subjects factors) and interactions involving task type (the between-subjects factor). Interactions involving task type were of primary interest in testing whether the main effects and interactions involving driving and auxiliary task difficulty were similar for the two auxiliary tasks or whether they were dependent on the specific characteristics of the auxiliary task. Hence, analyses of the interactions involving task type were the key to determining the role of task resource structure on intrusion. As a result of the mixed experimental design used, tests for main effects of task type were statistically less powerful than tests for interactions involving task type. However, direct comparisons between the Perception task and the Memory task were not very meaningful since the nature of the two tasks was very different.

Several analyses of variance were run using SAS procedures. Although the analyses examined all of the main effects and interactions involving the three independent variables, the emphasis was placed on testing interactions involving the variable, task type. In the majority of the analyses, interactions involving task type were not significant at the 0.01 level of significance. There were, however, five analyses in total in which task type was found to interact with other factors. These results are reported under the headings; driving performance, attention, and auxiliary task performance. Although the emphasis was placed on the analysis of interactions involving task type, where such interactions were observed, all of the 3-way effects are presented.

5.3.1. Driving Performance

The results of a 3-way ANOVA (task type X treatment X curve type) are shown in Table 13. In the top half of the table, baseline data were included in the analyses and designated as a fifth treatment condition (2 X 5 X 4); in the bottom half of the table, the baseline data were omitted from the analyses, leaving four treatment conditions corresponding to the four levels of auxiliary task difficulty (2 X 4 X 4).

Comparison of Table 13 with Tables 3 and 5 of Experiment One indicates that the overall pattern of effects on the driving measures reported earlier was replicated. This observation should be interpreted with caution, however, since Experiment Two in fact contained the data of Experiment One as a subset. There were a few notable differences. For example, unlike the results of Experiment One, the combined data did not replicate the finding that task difficulty affected headway, perhaps due to higher variability in the data. Also, the combined data exhibited a significant main effect of road curvature on the standard deviation of lane position ($F_{3,54}=4.38$) which was not exhibited by the Perception group data. Notwithstanding these differences, the results indicate that driving performance was affected by the presence of an auxiliary task. The results also affirm that road curvature had a significant effect on driving performance whereas the difficulty of the auxiliary task had relatively no effect.

The 2 X 5 X 4 analysis of variance revealed a marginally significant curve type X treatment X task type interaction ($F_{12,216}=2.22$, $p<.012$) for the variable, std. dev. of velocity. Further analysis revealed that this 3-way interaction was only present when baseline data were included in the data set. Hence, the interaction was confined within the baseline data.

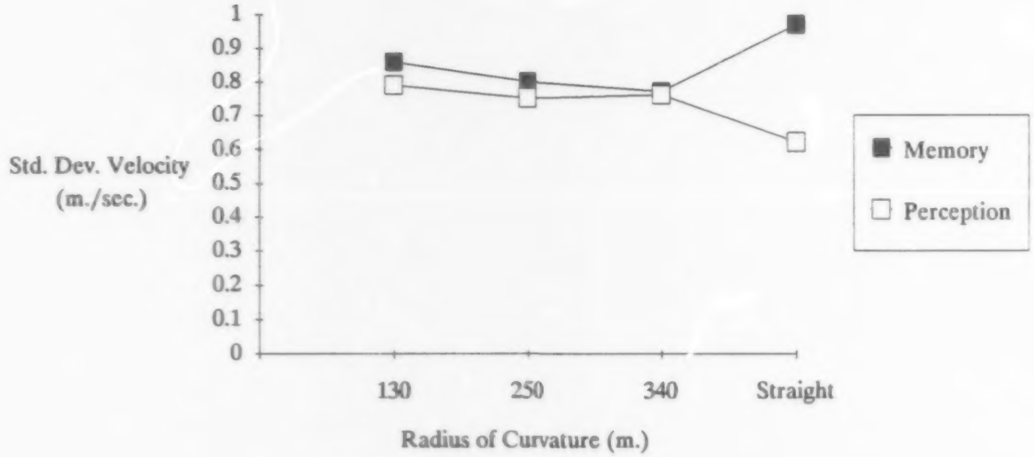
Figure 18 depicts the 2-way interaction, curve type X task type, for the baseline data. This figure indicates that the interaction was due primarily to the divergence of the baseline std. dev. of velocity data of the two groups of subjects for straight curves. The baseline data for the Perception task group presented the predicted pattern; i.e., std. dev.

velocity decreased monotonically with increasing radius of road curvature. In other words, as the driving task became increasingly less demanding, driving variability decreased. In contrast, the Memory task group exhibited a sharp and inexplicable increase in std. dev. velocity for straight curves. This interaction cannot be readily explained, since the data represent single-task driving in which there were no auxiliary task to perform - i.e., both groups of subjects experienced the same conditions. Notwithstanding the lack of a satisfactory explanation for this interaction, it is apparent that it does not signify a real task-dependent effect, since the interaction was manifest only in the baseline data.

Table 13: Summary of 2 X 5 X 4 and 2 X 4 X 4 ANOVA's

Source of Variation		TLC	EXC	SDLP	HDWY	SDVEL
TASK	F(1,18)	0.93	0.09	0.45	1.82	2.90
CRV	F(3,54)	93.68*	2.51	6.13*	2.54	0.42
CRV*TASK	F(3,54)	0.93	1.99	0.49	0.46	0.80
TRT	F(4,72)	35.10*	6.84*	23.03*	1.73	8.56*
TRT*TASK	F(4,72)	0.47	0.45	1.31	1.76	1.38
CRV*TRT	F(12,216)	4.59*	0.74	1.79	0.53	1.97
CRV*TRT*TASK	F(12,216)	1.09	1.54	1.00	1.21	2.22
TASK	F(1,18)	1.05	0.11	0.52	1.86	2.86
CRV	F(3,54)	70.85*	2.24	4.38*	1.13	0.44
CRV*TASK	F(3,54)	1.17	1.89	0.36	0.62	1.75
TRT	F(3,54)	3.25	2.70	2.59	1.23	3.18
TRT*TASK	F(3,54)	0.31	0.53	1.69	3.00	1.56
CRV*TRT	F(9,162)	1.05	0.61	1.90	0.28	2.39
CRV*TRT*TASK	F(9,162)	1.09	1.58	0.67	1.46	1.59

Figure 18: Baseline Condition



In summary, these results do not provide any evidence that the resource structure of the auxiliary task had any effect on driving performance under dual task driving.

5.3.2. Attention

The results of 3-way ANOVA's (task type X treatment X curve type) of attention variables are shown in Table 14. It should be noted that due to missing data resulting from the fact that subjects did not always view the auxiliary display under all experimental conditions, the analysis of dwell time was based on the data of 19 subjects. As a result, the degrees of freedom shown in the table do not apply to the variable, DWELL. The denominator degrees of freedom applicable to DWELL are shown in parentheses following the F value.

The effects of driving and auxiliary task difficulty on attention were consistent with the effects reported in Experiment One. However, readers should again recall that the present data include the data of Experiment One. The table indicates that, whereas all of the attention variables were highly affected by road curvature, they were relatively unaffected by auxiliary task difficulty.

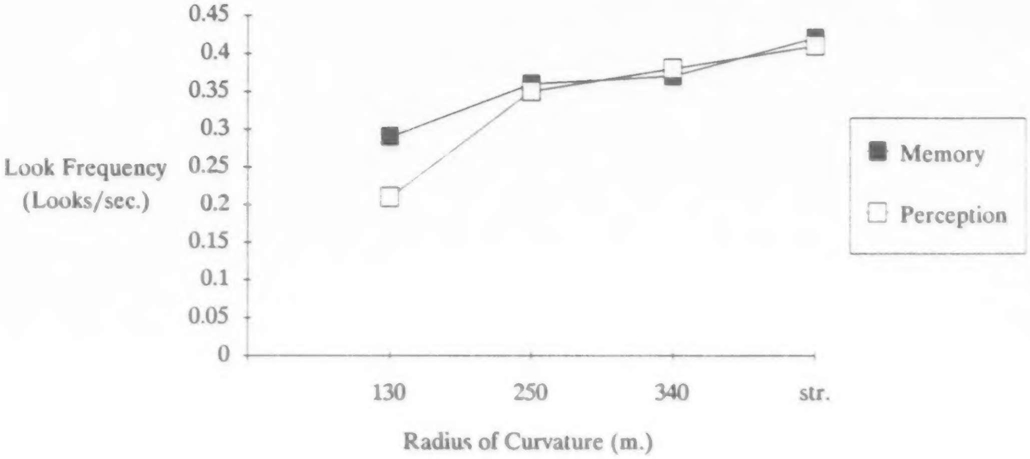
The 2-way interaction between curve type and task type was marginally significant for look frequency ($F\ 3,54 = 3.6$, $p < 0.02$), as indicated in the table. This interaction is graphically depicted in Figure 19, showing the effect of road curvature on look frequency for the two groups. It is clear from this figure that the interaction is primarily due to the divergence of the two curves at the highest level of road curvature. That is, for roads with a radius of curvature of 130 metres, the subjects in the Perception group looked less frequently at the auxiliary display than subjects in the Memory group. At all other levels of road curvature, the rate at which subjects looked at the auxiliary display was the same for both groups of subjects.

Table 14: Summary of 2 X 4 X 4 ANOVA of Attention Variables

Source of Variation		DWELL	LFREQ	VR
TASK	F(1,18)	0.04 (17)	0.50	0.66
CRV	F(3,54)	18.58* (51)	38.35*	135.23*
CRV*TASK	F(3,54)	0.68 (51)	3.60	2.65
TRT	F(3,54)	3.43 (51)	0.26	1.24
TRT*TASK	F(3,54)	2.22 (51)	0.67	1.26
CRV*TRT	F(9,162)	1.39 (153)	0.86	1.50
CRV*TRT*TASK	F(9,162)	0.87 (153)	0.81	1.93

The reason for the divergence of the look frequency data for the two groups is not clear, though several possible explanations can be proposed. Perhaps the most likely explanation is that the Perception task was more visually intensive and required subjects to fixate the display for a slightly longer period during each glance. Perhaps because this task required subjects to make visual comparisons among displayed elements, it may have been inefficient to attempt to acquire the displayed information over multiple glances. Assuming this were so, over sharp curves, there were fewer opportunities to glance safely at the auxiliary display for the requisite minimum time. The result was that subjects looked less frequently at the auxiliary display for this particular task at this particular level of driving difficulty. Further exploration of the differences in task characteristics that may have precipitated this interaction was beyond the scope of the study, since the Perception task and the Memory task differed along several dimensions, rendering direct comparisons not especially meaningful.

Figure 19: Curvature-Task Interactive Effects on Look Frequency



Whatever the true reason for the observed interaction, the effect was clearly confined within a small portion of the data (i.e., one level of road curvature). What is perhaps a more germane observation is that both tasks elicited generally the same attentional response - i.e., look frequency increased with decreasing difficulty of the driving task. The interaction, important as it may be in demonstrating some degree of attentional dependency on task characteristics, does not detract from the overall main effects which were largely task independent.

Interestingly, the dwell time data, shown in Figure 20 for both tasks, provided no evidence that dwell time was dependent in any way on task characteristics. Both tasks produced similar dwell time data at all levels of road curvature The similarity of the dwell time profiles for the two tasks indicates either that the demand for visual attention of both tasks were identical or that dwell time is independent of the characteristics of the auxiliary display. The former explanation is unlikely, since we observed some divergence in the glance frequency data. It would appear that the duration of fixations on auxiliary displays is determined primarily by the demands of the driving task.

5.3.3. Auxiliary Task Performance

Only 14 subjects responded to the auxiliary task under all experimental conditions. Since repeated measures analyses cannot handle missing data, records with missing data were omitted from the analysis. The results of a 3-way ANOVA (task type X treatment X curve type) for 14 subjects are shown in Table 15. General Linear Model (GLM) procedures were used to perform the analysis of variance since missing data led to an unbalanced design. NEGRT is the negative logarithmic transform of reaction time for correct responses to negative displays. (This transform was used to ensure homogeneity of variance.) Ignoring for the moment the interaction involving task type, the main effects of driving and auxiliary task difficulty are consistent with the results reported in Experiment One.

Figure 20: Dwell Time

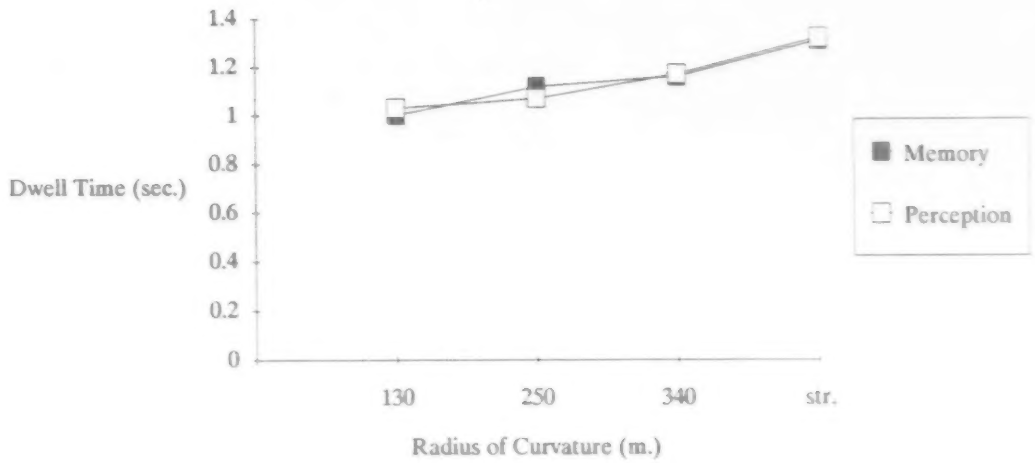


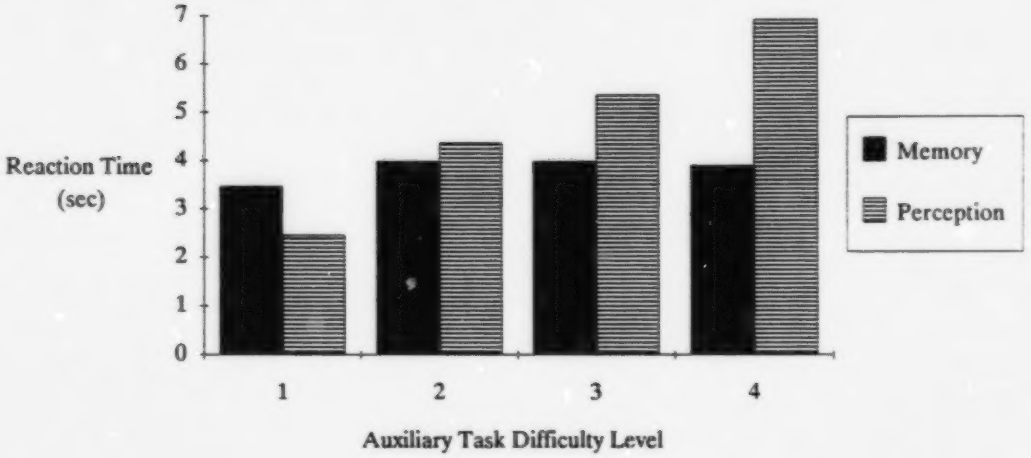
Table 15: Summary of 4 X 4 ANOVA of Auxiliary Task Performance

Source of Variation		NEGRT
TASK	F(1,12)	0.00
CRV	F(3,36)	10.49*
CRV*TASK	F(3,36)	1.20
TRT	F(3,36)	32.69*
TRT*TASK	F(3,36)	20.70*
CRV*TRT	F(9,108)	1.26
CRV*TRT*TASK	F(9,108)	1.63

The analyses of variance for the variable, NEGRT, revealed the presence of a significant treatment X task type interaction (F 3,36=20.70).

Figure 21 is a bar graph showing the 2-way interaction between task difficulty and task type. Whereas reaction time for the Perception task increased sharply with task difficulty, the reaction time for the Memory task remained relatively constant across all of the task difficulty levels. In interpreting this interaction, it is instructive to recall that the measure of reaction time reflects the sum total of the latencies associated with visual search, decision time and response selection and execution. The observation that reaction times remained relatively constant across all levels of Memory task difficulty suggests that decision time and response selection and execution were the predominant elements of reaction time for the Memory task. That is, the increase in memory search time that is known to occur with the increase in memory set size must be negligible by comparison to the times required for the other elements of the response cycle. In contrast, the increase in reaction time with task difficulty that was observed for the Perception task would indicate that visual search was an important element of the response cycle for the Perception task. This is consistent with the earlier contention (made to explain the task type X curve type interaction for look frequency) that the Perception task was more visually demanding than the Memory task.

Figure 21: Task-Difficulty Interactive Effects on Auxiliary Task Performance



5.3.4. Serial versus Parallel Effects

In Experiment One, evidence for the presence of parallel effects was undermined by an apparent confounding between attention and driving. This experiment provided an opportunity to revisit this issue through analysis of interactions involving task type. The role of divided attention as an important source of interference in driving could be established if a task type X treatment interaction were obtained. Specifically, under the assumption that simultaneous processing of two tasks is more efficient if the two tasks differ with respect to processing codes, certain a priori predictions can be made. Under control conditions, there is no reason to expect differences to exist between the two tasks, since both groups performed the identical viewing task (any differences being due to residual between-group variance). However, under the other dual task conditions, the Perception task was expected to produce relatively more interference than the Memory task because of greater competition for processing resources. Notwithstanding multiple resource predictions about the nature of the interaction, the reader should note that if indeed information processing capacity is differentiated then one would expect an interaction simply because the two tasks were structurally dissimilar.

Three-way analyses of variance were performed on the driving and attention variables. The results are presented in Table 16. The top half of the table provides resultant F ratios for the driving measures; the bottom half provides these data for the attention measures.

Table 16: Summary of 2 X 5 X 4 ANOVA's

Source of Variation		TLC	EXC	SDLP	HDWY	SDVEL
TASK	F(1,18)	0.73	0.16	0.44	2.47	1.55
CRV	F(3,54)	6.90*	3.16	6.62*	0.52	2.07
CRV*TASK	F(3,54)	0.98	0.41	1.46	1.57	2.53
TRT	F(4,72)	72.29*	2.77	6.26*	2.05	0.86
TRT*TASK	F(4,72)	0.74	2.20	0.76	0.37	1.26
CRV*TRT	F(12,216)	1.06	0.63	1.77	0.30	2.04
CRV*TRT*TASK	F(12,216)	0.96	1.29	0.75	1.24	1.40

Source of Variation	df	DWELL	VR	LFREQ
TASK	F(1,18)	0.11 (17)	0.45	0.40
CRV	F(3,54)	27.8* (51)	125.48*	33.95*
CRV*TASK	F(3,54)	0.86 (51)	2.01	2.48
TRT	F(4,72)	3.76* (68)	7.22*	3.59*
TRT*TASK	F(4,72)	1.29 (68)	1.14	0.62
CRV*TRT	F(12,216)	1.2 (204)	1.69	1.52
CRV*TRT*TASK	F(12,216)	0.70 (204)	1.45	1.34

The table indicates that auxiliary task condition, TRT, significantly affected both driving variables (i.e., time to line crossing and std. dev. lane position) and attention variables (i.e., dwell time, look frequency and viewing ratio). The five levels of auxiliary task condition included four levels of task difficulty and the control task (viewing task). Contrasts between the control condition and the other auxiliary task conditions (for these variables) indicated that the control task data were significantly different from the data corresponding to task difficulty levels 2, 3 and 4, but not from difficulty level 1 ($p < 0.01$). These results are similar to the results reported under Experiment One.

It is important to note that, in support of the null hypothesis, task type did not interact with treatment. These results, therefore, fail to support multiple resource predictions that task resource structure is important to task intrusion on driving. The results also fail to demonstrate the existence of parallel processing, since the attention and driving performance data of both groups were similar despite fundamental task differences.

Figures 22 and 23 depict the effect of treatment on time to line crossing and std. dev. lane position, respectively. Driving performance was slightly (but significantly) better under the control condition than under the three most difficult task conditions. Similarly, Figure 24 shows the relationship between viewing ratio and auxiliary task condition. This figure indicates that viewing ratio was markedly lower for the control condition than for the other task conditions. Hence, the treatment effect on driving was probably due to the subjects' reduced level of attention rather than to a fundamental difference between the control task and the auxiliary task which could be attributed to parallel processing. The attention hypothesis is given more credence by other trends in the data. Qualitative comparisons of group means at each of the four levels of auxiliary task difficulty suggest that subjects in the Memory group consistently performed the driving task less well than subjects in the Perception group; however, they also consistently viewed the auxiliary display more than their counterparts.

In summary, auxiliary task resource structure (e.g., processing code and stages) had no detectable effect on attention and driving data. In drawing this conclusion, it is important to recognize that, because our interest was directed at visual displays, we have not examined the potential role of display modality. That is, while multiple resource theory predictions did not hold under present experimental conditions, other models or dimensions (perhaps as yet unformulated) of differentiated capacity may prove more relevant. In particular, the potential advantages and limitations of auditory displays warrants careful study. Nonetheless, the forgoing results strongly suggest that, for visual auxiliary tasks, time sharing is a serial process.

Figure 22: TLC as a Function of Auxiliary Task Condition

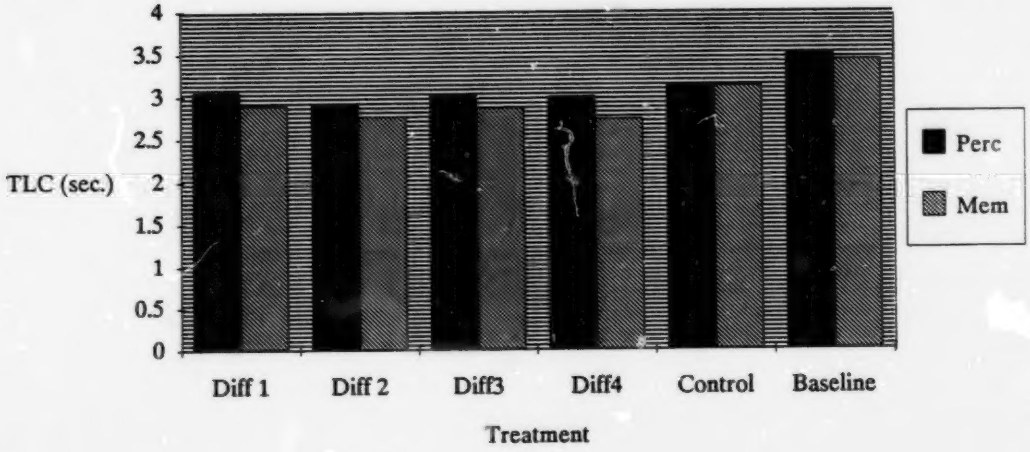


Figure 23: Std. Dev. Lane Position as a Function of Auxiliary Task Condition

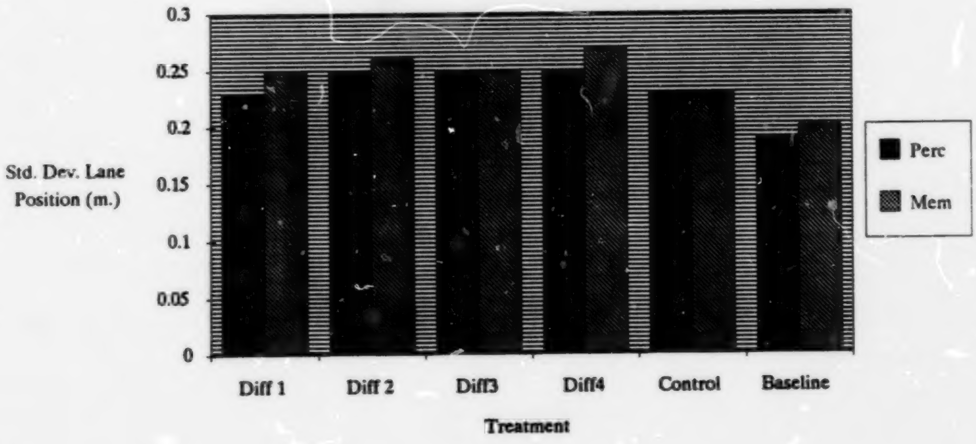
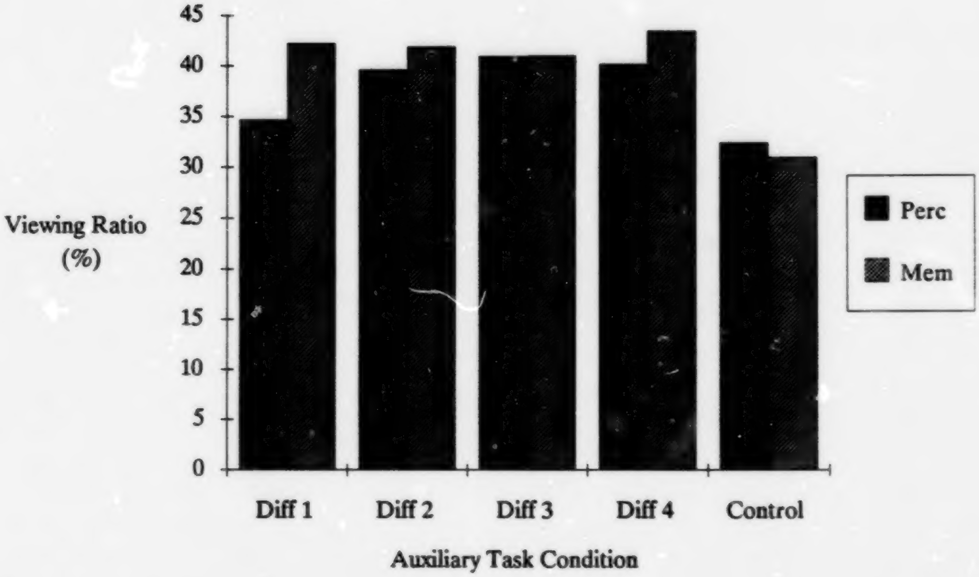


Figure 24: Viewing Ratio as a Function of Auxiliary Task Condition



5.3.5. Field Dependence

Further analyses were conducted to investigate the role of field dependence on subjects' selective attention and driving. The twenty subjects were divided, on the basis of the basis of the median EFT score, into two equal groups. A series of 4-way ANOVA's was used to test for the effects of field dependence. None of the analyses produced significant main effects or interactions for field dependence. The interaction of field dependence with curve type approached the criterion level of significance for the variable, headway (F 3,48=3.05, $p<0.04$), consistent with the results reported under Experiment One.

There is no evidence that field dependence had any effects on subjects' attentional response or driving performance. In drawing this conclusion, however, it should be noted that subjects were not screened on the basis of their EFT scores. Moreover, readers should note that the road scene was not visually complex.

5.3.6. Gaze Direction

Paired comparisons were performed to determine the effect of gaze direction (looking-inside vs. looking-outside). The results are shown in Table 17.

The results reinforce the results reported earlier, namely that driving quality was better when subjects looked inside the vehicle than when they looked at the road. Interestingly, in the present study, significant TLC differences were observed in concordance with the other measures of driving. (In Experiment One, the paired comparison test for TLC did not attain criterion level of significance).

Table 17: Paired T-Test Results for 'Inside' and 'Outside' Looking Conditions

Variable	Mean	Std Dev	T	Prob>|T|
TLC	0.15	0.69	5.10	0.001 *
EXC	-0.02	0.04	-10.00	0.001 *
SDLP	-0.03	0.08	- 8.72	0.001 *
HDWY	-0.63	12.25	- 1.07	0.287
SDVEL	-0.09	0.28	- 6.98	0.001 *

5.3.7. Mental Workload

Two-way ANOVA's were performed to examine the sensitivity of subjective workload ratings to varying levels of auxiliary task difficulty. The results, summarized in Table 18, indicate that the variable, Mental Demand, was the most sensitive of the 7 measures of workload, though TLX was also found to be sensitive to differences in auxiliary task difficulty (in contrast to the results of Experiment One). Despite the fact that TLX is claimed to represent a normalized composite measure of workload, the variable, Mental Demand, appears to be a more reliable measure of workload for applications involving the evaluation of auxiliary automotive displays.

Table 18: Summary of ANOVA of Workload Scales

Source of Variation		TLX	MD	TD	PD	E	P	F
TASK	F(1,18)	3.42	4.54	1.84	0.12	0.54	1.16	1.25
Difficulty	F(3.54)	4.42*	5.45*	0.94	0.71	2.36	0.98	1.42
Difficulty*TASK	F(3,54)	0.88	0.90	1.07	1.30	2.05	0.80	0.33

The table does not provide any evidence that task type affected any of the workload measures. This suggests that, despite their resource structural differences, the two tasks produced similar levels of workload. This was not surprising in view of the fact that the Memory task was modified to match the difficulty levels presented by the Perception task. In addition, the absence of a significant task type X task difficulty interaction, indicates that the effects of difficulty manipulations on the various workload measures were unaffected by the specific nature of the auxiliary task.

5.4. DISCUSSION

5.4.1. Task Resource Structure

Emphasis in the analysis of the results of Experiment Two was put on the identification and analysis of the interactions involving task type. Multiple resource theory predicted that tasks involving verbal/memory resources would be less intrusive on driving than tasks involving spatial/perceptual resources because they shared relatively fewer resources with the driving task. If resource structure were relevant to dual task interference in driving then task type should have interacted with other variables such as auxiliary task difficulty.

In only two of the several analyses that were performed was task type found to interact significantly with other factors. In the first instance, std. dev. of velocity was affected by a 3-way interaction (task type X curve type X treatment). However, upon further analysis, it was found that this interaction was confined to the baseline data; therefore, it was not considered relevant to the structural makeup of the auxiliary task. The other instance involved a 2-way interaction between curve type and task type for look frequency. Further analysis revealed this interaction to be confined within a small portion of the data (i.e., one level of road curvature). The failure to detect a more consistent pattern of interactions involving task type suggests that the effects of driving difficulty and auxiliary task difficulty on visual attention and driving performance are largely independent of the resource characteristics of the auxiliary task.

We may conclude, therefore, that resource structure is not relevant to the issue of auxiliary task intrusion on driving. The most likely reason for this result is that the sharing of attention while driving is primarily a sequential process, not subject to factors affecting simultaneous processing. Wickens and Yeh (1986) noted that multiple resource theory may not be applicable when independent tasks are performed in sequence. This conclusion may only apply to visual auxiliary tasks which force drivers to selectively attend to one display at a time. (Readers should note, however, that the processing of messages from auditory displays may be also subject to sequential processing limitations despite the removal of simultaneous competition for foveal vision. Readers should also note that the sequential nature of visual attention did not necessarily preclude the possibility or importance of simultaneous processing since drivers have been shown to exercize positive vehicle control during periods of visual inattention (Zwahlen and Balasubramanian, 1974).) Further evidence for the sequential nature of time-sharing in driving is derived from comparisons of the different task conditions with the control condition. The slightly better performance observed under the control condition was attributed to higher overall levels of viewing rather than the removal of demands for cognitive processing, suggesting that the act of looking away from the road was more important than what occupied the subject during those looks.

This is of great practical significance because it implies that auxiliary visual tasks, which may differ in terms of resource and other characteristics, can be expected to produce similar effects on drivers' attention and performance. It is worth restating that this result may only apply to auxiliary tasks that are presented on dash-mounted visual displays. This is not to say, however, that characteristics of display design are unimportant. As we shall describe later, there are some data to suggest that factors such as display legibility do affect drivers' attentional response. But, we must hasten to add that we have found no evidence that such factors affect driving.

In summary, task resource structure appears to have had relatively little impact on the level of auxiliary task intrusion on driving that was observed. It follows from this that the results of Experiment One can be generalized to other tasks that are presented on auxiliary visual displays.

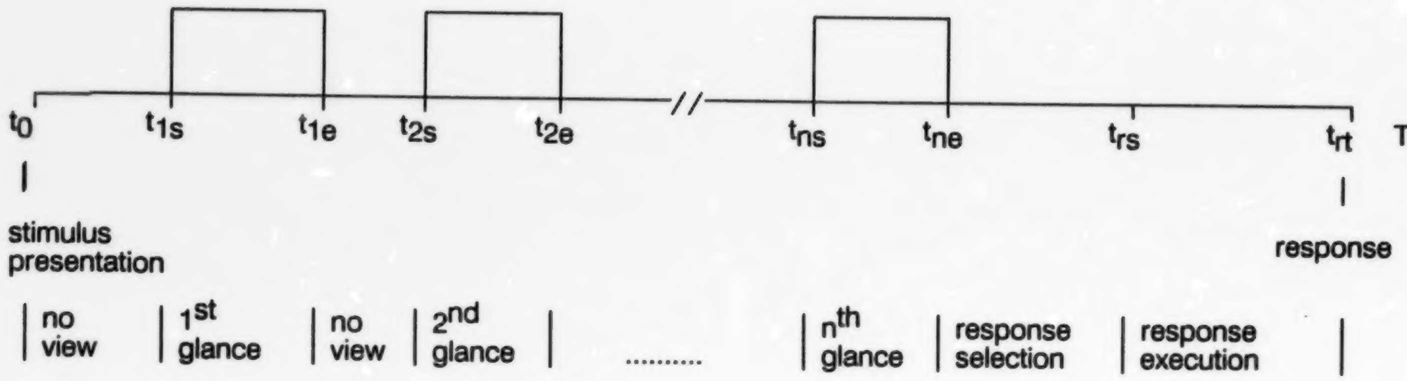
5.4.2. Generalized Response Cycle

The interaction obtained for look frequency was judged not to have had a large impact on the data, but it may be of theoretical interest to display designers. It was noted that a similar interaction was not obtained for dwell time. A number of questions arise concerning individual measures of attention and their interrelationships because of their specific influence on display effectiveness. Such interrelationships may become especially important under conditions in which the human operator is overloaded. Although investigation into these relationships was beyond the scope of the present study, the data do provide some insight into possible attention mechanisms which could influence display effectiveness. The predominant factor underlying these relationships is the conflict that arises between what have been termed the "data acquisition algorithm" and the "scheduling algorithm" of the human observer (Moray, 1986) when there isn't sufficient time to acquire all of the desired information. Although our data did not permit detailed analyses of the relationships and tradeoffs between dwell time and look frequency, certain tentative principles based on insights gained from the data are described below. But first, it is instructive to develop a simple model of a generalized response cycle to help identify the various elements.

For any particular task, one can divide the response cycle, at least conceptually, into several distinct phases. Figure 25 is a time line showing the composition and sequence of events of a generalized response cycle. The major components include 'no view' time (i.e., time not available for viewing the display due to preoccupation with primary task), viewing time which consists of one or more glances at the display, and response selection and execution following the acquisition of all of the relevant information. The total response time, the sum of the time intervals for the various events, is a function of the time available to view the display, the time actually taken to view the display, and the time necessary to select and to execute the appropriate response. The specific timing of each event depends upon a large number of task and environmental factors as well as the outcome of preceding events. The major task and environmental factors include; driving difficulty, the cognitive load of the task, and the motor load of the task.

The way in which task and environmental factors affect the different elements of the response cycle is of interest to the designers of displays because they influence display effectiveness. Studies into human monitoring behaviour are relevant to this subject. These studies have led to several models that describe the monitoring behaviour of the human observer (for a review see Moray, 1986) which differ with respect to the assumptions that are made, the variables predicted, the factors considered and their applicability to different situations. In his chapter, Moray (1986) notes the factors which influence the monitoring behaviour most are (a) the statistics of the observed process, and (b) the subjective appreciation of the intrinsic value of the task.

Figure 25: Response Cycle


t_0
t_{1s}
t_{1e}
t_{2s}
t_{2e}
t_{ns}
t_{ne}
t_{rs}
t_{rt}
Time
stimulus presentation
response
no view
1st glance
no view
2nd glance
....
nth glance
response selection
response execution

5.4.3. Mechanisms of Attention

The notion that time-sharing while driving is a sequential process in which attention is focused on one task at a time prompts one to consider the relevance of queueing theory-based models of human monitoring behaviour for describing the attentional responses of drivers (Carbonell, 1966; Senders et al., 1964). It should be stressed, however, that the main purpose of this study was not to develop or validate models of drivers' attentional behaviour during time sharing.

The majority of such models are based on information theoretic principles. They relate variables such as dwell time, sampling frequency and transition probabilities to the information content and bandwidth of information sources. Direct application of human monitoring models to driving is difficult, since the road view is a composite of several sources of information and our knowledge of the relevant visual cues is at best incomplete, as are techniques for quantifying the information content of any particular source. Senders et al. (1967) derived an uncertainty model of driving and attempted to validate the model by comparing predicted occlusion times with observed values in a series of studies. However, the derivation of drivers' uncertainty of lateral position, which is central to the model, has been impugned (Zwahlen and Balasubramanian, 1974). The monitoring models, however, advance certain principles which may be important to our understanding of drivers' attentional response and which can be evaluated qualitatively. In this section we will attempt to relate these principles to our data.

According to the Periodic Sampling Model of Display Monitoring of Senders et al. (1964), dwell time is proportional to the average information content of the display. The present results, however, indicate that the mean duration of fixations on the auxiliary display was determined not by the information content of the display but rather by the attentional demands of the driving task. These data appear to contradict the model's predictions for dwell time (for the auxiliary display). However, it is essential to note that the model of Senders et al. assumes that all of the information displays are equally important and that the human observer has sufficient time to view them all. In the present experiment these assumptions were not tenable. Driving appears to have been given sufficient priority that the information content of the auxiliary display was overshadowed by the attentional requirements of the driving task. The model of Senders et al. does not make allowances for the emphasis on driving. In this regard, the model of Carbonell (1966) may be more applicable, since it incorporates utility concepts such as the relative importance of individual displays, the costs incurred to sample the display, etc., though Carbonell's model does not predict dwell time.

Uncertainty models have enjoyed wide acceptance among driving researchers. (Uncertainty models have also led to the development of time to line crossing as a representation of drivers' attentional strategy in driving.) The occlusion technique, for example, is based upon uncertainty principles and has been shown to be a useful technique for quantifying the attentional demands of driving (Blaauw, 1984; Senders et al., 1967; Zwahlen and Balasubramanian, 1974). Given that dwell time was determined primarily by the time that could be spared from monitoring the road display, it may in fact be valid to extend the results of occlusion studies to dual task applications.

Information-theoretic concepts have recently been extended in the development of a Supervisory Driver Model (Blaauw, 1984; Godthelp et al., 1984). The Supervisory Driver Model was derived from Optimal Control Theory and incorporated elements of the Optimal Control Decision Model (Kok and Stassen 1980, for control of slow processes). Although perhaps the name of the model might incorrectly convey the notion that the driver is supervising the driving process, this model extends previous man-in-the-loop models of driving (for a review see Reid, 1983) by recognizing the multitask nature of driving and designating lane tracking as the primary task (not the only task). The model comprises three main blocks; a preview/predictor block, a control block and a decision block. The driver previews road geometry and predicts vehicle trajectory relative to the desired vehicle path. The driver may decide to allocate attention to non-tracking tasks (via the decision block) when he/she is reasonably sure that the vehicle is on course. The driver redirects attention to the tracking task whenever his/her level of uncertainty rises above a criterion level. A limitation of the model is that it does not make any provisions for the performance of non-driving tasks during periods of inattention. With respect to attentional behaviour, the results of the present study suggest that this limitation is less important than initially thought. However, the model also makes the implicit assumption that non-driving tasks do not intrude on the driving task. That assumption, as we have seen, is less tenable.

The model of Senders et al. predicts that the frequency at which displays are sampled is proportional to the bandwidth of the signal (specifically, sample frequency is 2W times/sec. where W is signal bandwidth in Hz.). Since, in the present study, look frequency measured the rate of transitions between the road display and the auxiliary display, look frequency was in fact the sampling rate for both the forward and the auxiliary displays. As such, it reflected a balance between the sampling requirements of the two tasks. The auxiliary display had infinite bandwidth yet low priority. Therefore we can assume that the increase in look frequency that we observed with decreased road curvature reflected a diversion of attentional resources from the road to the auxiliary display (to serve the infinite queue) as the bandwidth of the road display dropped. This conclusion is consistent with the earlier discussion.

It would appear logical that when attentional capacity is nearly saturated dwell time and look frequency are highly interactive. That is, the information displayed on a particular display can be acquired either through one long glance or through a series of shorter glances, depending upon the specific task-sharing circumstances. However, the tradeoff between look frequency and dwell time is not simply a matter of time equivalence. It was suggested earlier, for example, that subjects may have found it inefficient to use multiple glances when dwell time was below some critical value (which was task dependent). Such inefficiencies may arise, for example, from the additional time necessary to refocus attention at the beginning of each glance. Hence, one glance of t sec. duration may transmit a great deal more information than 2 glances of 1/2 t sec. duration each, and so on. The interdependence of these variables, therefore, relates to such factors as the number and size of time chunks available for viewing, the amount of information contained in the display, the nature and importance of the task, information loss between successive looks and the time cost of looking.

The present data suggest that the primary factors affecting look frequency may in fact be different from those affecting dwell time (in line with Senders' et al. model, 1964). As described earlier, dwell time appears to be highly sensitive to the characteristics of the driving task and, to a lesser extent, also sensitive to the specific characteristics of the auxiliary task. Moreover, the absence of interactions involving task type for this variable, despite basic structural differences between the two tasks, confirm that the perceptual/cognitive characteristics of the auxiliary tasks were of little consequence.

Nevertheless, it seems logical that dwell time must have some general dependence on the nature of the auxiliary task. In fact, the data of Experiment One showed that dwell time did increase slightly with auxiliary task difficulty. In theory, there is a lower bound for dwell time below which so little information can be acquired, or accumulated, that the probability of its occurrence is very small. For example, subjects' unwillingness to make short inefficient glances may explain the interaction between task type and curve type that was observed for look frequency in the present experiment. (That is, the time available for viewing the auxiliary display on 130-metre curves was insufficient for subjects to acquire the information necessary for response selection (for the Perception task) thus inhibiting overall sampling rate for this condition.) In this way, display factors such as processing codes and display legibility may influence display effectiveness, but do not necessarily contribute to task intrusion on driving.

At the other extreme, above some upper limit of dwell time, no additional information can be acquired from the display; hence, the probability that dwell time exceeds this limit is similarly small. It would appear, therefore, that dwell time can be regarded as bounded within a broad range of values appropriate to the task. Within that range, the specific value depends upon the momentary demands of the driving task.

Look frequency, on the other hand, reflects, among other things, the need to obtain additional looks when the driver is unable to acquire all of the necessary information in one glance. Its dependency on dwell time stems from the fact that the auxiliary task was a discrete self-paced choice reaction time task. In other words, its bandwidth was essentially infinitely large. We have also noted that because the auxiliary task was intended to capture all of the subjects' spare attentional capacity, look frequency reflected certain properties of the driving task. According to the Senders et al. (1964), display sampling frequency is proportional to display bandwidth. However, we noted that in this special case, look frequency reflected the requirements of both tasks (appropriately weighted). Because driving was given priority, we may infer that the look frequencies were at least twice the bandwidth of the road display and probably higher (to maximize sampling of the auxiliary display). In summary, we speculate that look frequency depends upon the choice of dwell time in relation to the visual complexity of the task (e.g., perceptual/cognitive load), driving difficulty and the time and complexity of output processes that may be required to complete a response.

In previous studies of driving, viewing ratio, i.e., the proportion of total time devoted to an auxiliary display, was often used to measure attentional supply or demand (Antin et al., 1986a; McDonald and Ellis, 1975). But, the foregoing discussion suggests that viewing ratio is not necessarily the most sensitive indicator of task intrusion on the driving task. Viewing ratio is the product of variables which may be influenced differently by different aspects of the task-sharing requirements. Dwell time and look frequency appear to reflect different aspects of the attentional response, are differentially sensitive to different characteristics of concurrent tasks and their combination, and contribute differentially to the overall effect on task performance and mutual interference.

There may not be a single universal measure of attention that addresses all of the relevant effects of auxiliary tasks. Variables such as viewing ratio, look frequency, and dwell time may each have unique qualities, reflecting subjective task prioritization strategies to resolve conflicting data acquisition and scheduling requirements. The interrelationships between look frequency and dwell time, the factors affecting their interdependence and their differential effect on driving warrant further investigation.

6. EXPERIMENT THREE

6.1. PURPOSE

The results of the previous two studies were dependent to a large extent on the subjects' relative allocation of cognitive resources to the primary and auxiliary tasks. One factor which may have influenced subjects' resource allocation ratios was auxiliary task utility. It was recognized that both the Perception task and the Memory task that were used presented abstract tasks having limited intrinsic value for the subjects. Actual auxiliary tasks, on the other hand, can be expected to have greater utility than the tasks that were used thus far. For example, actual tasks associated with route guidance displays will assist drivers to navigate through unfamiliar territory and other auxiliary tasks will permit drivers to interact in a variety of ways with electronic systems and other drivers. The critical questions, therefore, concern the influence that task utility may have on drivers' resource allocation ratios and the extent to which this affects joint performance.

Two distinctly different predictions can be made concerning the effect of auxiliary task utility on the driver's resource allocation ratio, depending upon what assumptions one is prepared to make. Both can be supported by economic-theory based considerations (Navon and Gopher, 1979). One view is that resource allocation in driving is to some extent elastic and will therefore reflect the relative utility of the two tasks. That is, the nature of the tasks and their combination is such that it is possible to tradeoff performance on one task for performance on the other. The tradeoff is decided on the basis of utility considerations. Hence, increased utility of the auxiliary task will result in greater allocation of resources to the auxiliary task and, consequently, in degradation of driving quality. This prediction is perhaps more cogent for a driving simulator in which drivers may feel less compelled to maintain driving quality at a safe level than under real world conditions.

There is also some basis for predicting that increasing task utility will have no effect on driving. For example, applying economic-theoretic concepts of Navon and Gopher (1979), auxiliary task utility will be expected to have no effect if the subjective substitution rate, i.e., the utility tradeoff, is such that the gain from improvement of auxiliary task performance is low compared with the loss due to deterioration of primary task performance. This can occur, for example, if there is an overwhelming subjective preference for the driving task (e.g., due to intrinsic value for safety). Some evidence for a subjective preference for the driving task derives from the observation that drivers modulated their allocation of attentional resources in a way that maintained driving quality within narrow bounds. If, indeed, drivers are able to assess accurately the requirements of the driving task and direct the requisite attentional resources to the primary task, then auxiliary task utility may have little or no effect on the data.

The purpose of this experiment was to determine whether increasing the utility of the auxiliary task would result in increasing task intrusion beyond the levels observed in the previous experiments. Because the study was performed in a driving simulator, it was recognized that negative effects of increased auxiliary task utility on driving would require confirmation through field studies. On the other hand, it was considered that the absence of a negative effect could be generalized beyond the simulator.

6.2. METHODOLOGY

6.2.1. Experimental Design

Following general recommendations of Norman and Bobrow (1975) for the manipulation of task priority, the relative emphasis on the driving and auxiliary tasks was manipulated through monetary rewards given for good performance on the auxiliary task. Subjects retained maximum control over the quality of performance of both tasks. Restructuring the payoff matrix in this way was considered a valid manipulation of relative task utility since subjects volunteered to participate in the study primarily for monetary reasons.

Attention and Performance data were obtained for a new group of subjects, the Bonus group. These subjects performed the Memory task using the dual-task protocol described under Experiment Two. In contrast to the Memory subjects, however, the Bonus subjects received monetary bonuses which depended upon their performance of the auxiliary task. By combining the data from this group and the Memory group of Experiment Two, it was possible to test for the effect of task utility as a between-groups factor.

The within-subjects factors were auxiliary task difficulty and driving difficulty; the between-groups factor, bonus, was tested at two levels, bonus and no-bonus. Subjects in the no-bonus group, who were tested earlier, were simply instructed to perform the auxiliary task as well as possible - no rewards were given on the basis of performance on either task. Subjects in the bonus group were given rewards designed to encourage greater allocation of resources to the auxiliary task. Although they were instructed, as were the no-bonus subjects, not to allow the auxiliary task to interfere with their lane keeping or car following performance, they were, in fact, free to allocate all of their resources to the auxiliary task to maximize their monetary gains (though they were not told this explicitly). However, no rewards were earned nor penalties incurred on the basis of primary task performance. More complete details describing the bonus condition are provided in the sections which follow.

6.2.2. Experimental Protocol

The experimental apparatus and set-up are described under the appropriate sections of Experiments One and Two. The Memory task was used in this study because the variability in the data obtained for this group of subjects was lower than the variability for the Perception group. The data collected from this group of subjects were combined with those of the no-bonus group for statistical analysis. The only departure from the test protocol used in Experiment Two concerned the instructions pertaining to the bonus and its administration, as described below.

6.2.3. Bonus Condition

Subjects in the bonus group were given written instructions indicating that they would receive monetary bonuses if they performed the auxiliary task better than they did during task training - the better they did, the more they would receive. Specifically, they were advised that they would receive one dollar for each second by which their correct response time was better than a specific criterion level which represented their trained level of performance. The criterion level was determined for each subject from his/her training data and specified on the instructions form. For the control condition, subjects were instructed that they would receive one dollar for each percentage point that their viewing ratio exceeded their trained level of performance. Again, this level was determined from the training data and indicated on the instruction forms. Criterion levels of performance were adjusted slightly to guarantee that subjects would receive some bonus on most trials.

Subjects were reminded that driving was the primary task and not to allow the auxiliary task to detract from the driving. All subjects indicated that they understood how the bonus would be calculated and what they were required to do.

After each test trial, feedback of the auxiliary task performance (response latency) and the calculated amount of bonus that was earned was provided to the subjects. The provision of feedback served to remind subjects that they were rewarded for their performance on the auxiliary task and to convey some idea of the worth of additional effort. By comparison, subjects in the no-bonus group were not given any response latency feedback. Subjects in both groups received accuracy feedback as a means to ensure that they attained the required minimum level of accuracy on the auxiliary task (95%).

6.2.4. Subjects

Subjects were ten new student volunteers - five males and five females. None of them had participated in any previous experiments at UTIAS. One subject withdrew from the experiment due to simulator sickness and he was replaced. Subjects ranged in age from 19-36, with a mean age of 23.9 years. All of them had normal vision, a minimum of three years driving experience and owned their own vehicles. None of them had traffic offenses or were involved in traffic accidents during the previous three years. Subject testing and training followed the procedures described in Section 5.2.8.

Subjects were paid a nominal $100 for their participation in the study plus any bonuses to which they were entitled. They earned between $9.40 and $38.15 in bonuses, with an average bonus amount of $19.84.

6.3. RESULTS

Summary data are contained in Appendix A. The data were then combined with the data of the no-bonus group tested under Experiment Two. The resultant database represented a 3-way mixed design which was subjected to a variety of statistical analyses using SAS procedures.

6.3.1. Driving Performance

The results of a 3-way ANOVA (bonus X treatment X curve type) are shown in Table 19. The 4 levels of treatment correspond to 4 levels of auxiliary task difficulty.

Table 19: Summary of 2 X 4 X 4 ANOVA

Source of Variation		TLC	EXC	SDLP	HDWY	SDVEL
BONUS	F(1,18)	0.03	3.15	0.79	0.05	1.44
CRV	F(3,54)	56.56*	3.92*	6.78*	0.46	1.96
CRV*BONUS	F(3,54)	1.38	0.63	0.33	0.49	0.44
TRT	F(3,54)	2.63	0.50	1.33	0.12	2.44
TRT*BONUS	F(3,54)	6.96*	1.14	0.90	1.18	1.62
CRV*TRT	F(9,162)	2.03	0.90	1.65	0.65	2.51*
CRV*TRT*BONUS	F(9,162)	1.94	1.65	1.48	1.10	1.47

The results indicate that auxiliary task difficulty had little effect on the driving data (the treatment X bonus interaction for TLC will be discussed below). On the other hand, driving difficulty had a significant effect on lane keeping performance as in the previous experiments. The variable, bonus, did not contribute significantly to the variability of driving measures, indicating that subjects in both groups performed the driving task equally well under all conditions. Analyses of variance of subjects' baseline data indicated that between group differences did not contribute to variability of any of the single task driving measures, confirming that subjects in both groups were equally proficient in driving skills. The results, summarized in Table 19, indicate that bonus interacted with task difficulty for the dependent variable, TLC. Examination of the data indicated that TLC fluctuated within a small band, ranging between 2.7 to 3.1 sec. The values did not vary in any systematic way with either bonus or task difficulty level. Post-hoc comparisons indicated that the treatment x bonus interaction was due to the a small but significant difference at difficulty level 2, though it is hard to attach practical significance to this finding due to reversals in the other data. This singular result is therefore regarded as spurious and no particular significance is attached to it.

These data provide no evidence that auxiliary task utility contributed to its effect on driving.

6.3.2. Attention

The results of a 3-way ANOVA (bonus X treatment X curve type) for attention are shown in Table 20. It should be noted that due to missing data, resulting from the fact that subjects did not always view the auxiliary display under all experimental conditions, the analysis of the dwell time data was based on the data of 18 subjects. As a result the degrees of freedom shown in the "df" column of the table do not apply to the variable, DWELL. The denominator degrees of freedom applicable to DWELL are shown in parentheses following the F value.

The effects of driving and auxiliary task difficulty on attention were consistent with the effects reported under Experiment Two. However, readers should again recall that the present data include half of the data of Experiment Two as a subset. The table indicates that, whereas all of the attention variables were highly affected by road curvature, they were relatively unaffected by auxiliary task difficulty. Of particular interest to the present study is the result that none of the bonus main effects or interactions involving bonus were significant. Therefore, there is no evidence that allocation of visual attention was affected by the utility of the auxiliary task.

6.3.3. Auxiliary Task Performance

Analysis of variance was performed on transformed correct reaction time scores to test for effects due to task utility. The results, shown in Table 21, were based on data from 18 subjects, since observations with missing values could not be included in the analysis. Clearly, the results failed to show any effect that task utility may have had on auxiliary task performance.

Table 20: Summary of 2 X 4 X 4 ANOVA of Attention Variables

Source of Variation	df	DWELL	LFREQ	VR
BONUS	F(1,18)	0.11 (16)	0.52	0.12
CRV	F(3,54)	39.66* (48)	17.96*	73.80*
CRV*BONUS	F(3,54)	0.51 (48)	0.11	0.08
TRT	F(3,54)	1.52 (48)	0.64	0.10
TRT*BONUS	F(3,54)	1.06 (48)	1.23	0.61
CRV*TRT	F(9,162)	0.93 (144)	0.84	0.55
CRV*TRT*BONUS	F(9,162)	1.03 (144)	1.11	0.88

Table 21: Summary of 2 X 4 X 4 ANOVA of Transformed Correct Reaction Time (NEGRT)

Source of Variation	df	NEGRT
BONUS	F(1,16)	5.93
CRV	F(3,48)	25.05*
CRV*BONUS	F(3,48)	0.12
TRT	F(3,48)	8.67*
TRT*BONUS	F(3,48)	1.22
CRV*TRT	F(9,144)	0.72
CRV*TRT*BONUS	F(9,144)	1.16

6.4. DISCUSSION

The provision of bonus payments for improved auxiliary task performance failed to produce observable changes in primary task performance, attention or auxiliary task performance. The results of these analyses provide converging evidence that task utility had little or no effect on the resource allocation ratio. Hence, we conclude that the results of Experiments One and Two are generalizable to actual auxiliary tasks.

As discussed earlier, there are more than one possible explanation for this finding. Applying the economic concepts advanced by Navon and Gopher (1979), one possible explanation is that the nature of the two tasks provided no latitude for performance tradeoffs (i.e., that performance of the auxiliary task was data limited). However, the data indicate that auxiliary task performance under dual task driving was significantly below single task levels, thus refuting this possibility. Also, it cannot be argued that subjects' subjective substitution rate was such that it was not attractive for them to divert resources from the driving task to the auxiliary task. Subjects were paid for good performance on the auxiliary task and were not penalized for poor performance of the driving task. Evidently, subjects chose not to allow their driving to deteriorate any more than their counterparts who did not receive bonuses.

The reason that subjects were unaffected by the payoff manipulation, we believe, is that they experienced difficulty in overcoming a driving 'style' that has become internalized over years of experience. Driver expectancies concerning the resource demands of the driving task under a variety of conditions and his/her capacity to meet those demands affect the driver's attentional strategy. Expectancy has also been shown to have a profound influence on driver perception and assessment of risk (Hills, 1980). These strategies have been sufficiently practiced that they have become automatized to a large extent. We believe that driving in the simulator was real enough that subjects implemented these attentional strategies automatically. Further, these strategies are sufficiently automatized that they are not easily amenable to manipulation. Anecdotally, it is of interest to note that even when one is attempting to deliberately drive off the road in the simulator or towards stationary buildings, one experiences an initial reluctance.

These results indicate that subjects were unable or unwilling to alter their assessment of risk to reflect the realities of driving in a simulator. (It should be noted subjects had no exposure to other payoff conditions. Had the experiment been conducted purely as a repeated-measures design, an alternative explanation may have been asymmetric transfer.) The importance of an absence of a bonus effect is that it lends considerable credibility to simulation as a valid means for carrying out investigations into dual task driving. Had task utility significantly altered resource allocation in the simulator, the role of task utility may have been challenged on the basis that simulation elicited more elasticity in resource allocation than might be expected under real world conditions.

7. DISCUSSION AND CONCLUSIONS

Technological advances in in-vehicle information displays will have a profound effect on the complexity and sophistication of future driver interfaces. From a road safety perspective, the impact of advanced in-vehicle displays must be evaluated within the framework of the driver as an information processor, to minimize the risk of accident involvement due to driver inattention, distraction or increased workload.

This study comprised a series of three experiments performed in a driving simulator under controlled conditions to investigate some of the theoretic issues surrounding the design and use of in-vehicle displays. The study applied current theories of human performance and information processing to address critical issues posed by emerging automotive technologies. The experiments involved the analyses of 'modules' of data that were collected during different phases of the study. This building block approach and integration of modules was found to be efficient and derive maximum value from the experimental data. The subject of this study was sufficiently complex that it would not have been reasonable to incorporate all of the relevant factors into a single experiment.

The first experiment manipulated driving and auxiliary task load in a within-subjects design to study their combined effect on joint performance. The second experiment introduced a second auxiliary task to yield a mixed design which permitted assessing the relevance of resource structure to concurrent task performance in driving. In the third experiment, subjects received bonuses designed to alter their resource allocation ratio in an attempt to determine the role of task utility on the results. A standard paradigm was used throughout to permit data integration.

The subjects were well practiced and we have no reason to suspect that they performed the driving task differently than they would have in real traffic. They understood the instructions and appreciated the importance of the driving task. Despite the introduction of measures intended to produce shifts in task priority (i.e., through payoff manipulation), there was no evidence that these measures affected subjects' allocation of processing resources. This has important theoretical and practical implications. The theoretical implication is that drivers naturally attach priority to the driving task, they are reluctant to change their subjective preferences in task sharing situations and they endeavour to allocate attentional resources that are commensurate with the perceived demands of driving. The practical implication is support for the validity of simulator research. In the face of meaningful inducements, subjects demonstrated a reluctance to alter their 'style' of driving despite the complete absence of danger or monetary penalties for poor performance. Nonetheless, replication of these findings under field conditions would be required for validation.

The study makes important contributions to our understanding of factors affecting drivers' attention and performance under dual task conditions and demonstrates the usefulness of driving simulators for assessing the human factors aspects of in-vehicle displays.

The simulator paradigm that was developed and used in the course of the studies was sensitive to differences between single and dual task conditions as well as to changes in the levels of driving and auxiliary task load.

The theoretical framework presented in Chapter 3 guided the interpretation of results. It has been previously suggested that under open-loop driving, such as under occlusion, the driver exerts positive control on the basis of previewed information, internalized strategies and knowledge of the system dynamics (Godthelp et al., 1984; Zwahlen and Balasubramanian, 1974). When open-loop periods are occupied with the performance of another task, mutual interference between the two tasks may occur through the mechanisms of divided attention or focused attention. If the tasks are performed concurrently, then multiple resource theory may be relevant to the mechanisms producing interference.

Interestingly, both auxiliary tasks, despite major differences in resource structure, exhibited similar effects on subjects' attention and performance. Driving difficulty was found to have a much larger effect than auxiliary task difficulty. Although a significant difference was observed between the control condition and three levels of the auxiliary task, this effect could not be attributed to the cognitive elements of the task because the control task received significantly less attention. There was no conclusive evidence that processes which are known to affect concurrent information processing were relevant. The results suggest that the main source of interference was the need to attend to another task. However, it should be pointed out that it was not possible to distinguish between peripheral conflict (i.e., the physical need to move one's eyes) and focused attention (i.e., sequential processing at higher levels). The results suggest, however, that the time-sharing of driving with other visual tasks can be considered to be a serial process and is subject to single channel limitations. In practical terms, this might point towards the use of HUD's or auditory displays as a means of reducing conflicting demands on the visual system. However, these measures may not solve the problem if sequential processing is found to be localized more centrally within the human nervous system.

Driving measures such as time to line crossing and headway were particularly sensitive to changes in both primary and auxiliary task load. Interestingly, these two measures appeared to be most closely related to the visual cues employed for lane keeping and car following. It should be pointed out that the variable, time to line crossing, has only recently been formulated and has not been used in driving research outside of the Institute of Perception TNO, Soesterberg in the Netherlands (Godthelp, 1984; Godthelp, 1986; Godthelp et al., 1984). Our experience with this measure supports the claim that TLC is a useful quantitative indicator of driver performance. Its evolution from an extension of the preview-predictor model to include both closed-loop and open-loop strategies makes this measure especially relevant to studies of drivers' attentional behaviour. The importance of this variable is that it ascribes the driver's attentional behaviour, and therefore tracking performance, to his/her assessment of 'free time' (i.e., time available for neglecting tracking error). The results of the present experiments support the view that attentional response is determined primarily on the basis of driving demand.

Assuming drivers do indeed switch attention on the basis of perceived driving demands and that TLC is a valid measure of drivers' perception of 'free time', then it follows that dwell time should be proportional to TLC. To test this, the correlation between dwell time and TLC was examined. The Pearson correlation coefficient, $r=.19$, was significant ($p<.0001$). Although the correlation was small, it was significant and in the predicted direction. Of course, both dwell time and TLC were dependent variables and, therefore, it is not valid to infer cause and effect relationships from these data. However, it is important to note that the results support the validity of the assumptions underlying the construct of TLC.

Significant degradations in driving measures such as std. dev. of lane position, headway, and std. dev. of velocity were observed in these experiments to accompany the performance of an auxiliary task. It is important to recognize that in these experiments, subjects were instructed to maintain lane position and headway as constant as possible. The fact that there were reliable effects due to manipulations of independent factors is indication that they were not able to perform equally well under all conditions. This has to be recognized as a decrement in their driving quality.

To what extent such decrements can be expected to affect aggregate accident statistics in the real world is impossible to estimate, given our present state of knowledge about accident causation. There are no empirical links that could help interpret the safety impact, for example, of a 26% increase in lane position variability. It is not possible to identify the subset of accidents in which lane keeping variability was a contributing factor, especially those that could be linked to inattention, however defined. It is clear that the probability of lane exceedence is proportional to the standard deviation of lane position. However, it is very rarely the case that lane deviations result in collisions. Common experience affirms that drivers often knowingly deviate from the lane (e.g., when there is not danger of collision). The problem of quantifying the practical significance of these effects on the overall road safety picture does not detract from the fact that reliable effects are bound to have some impact.

While the absolute magnitude of the effect on certain of the driving variables may have been relatively small, it should be recognized that reliable effects signify a reliable increase in driver error probability. The reliability of the effect is what is important, not its magnitude, because of the magnitude of driving exposure.

Attentional variables provided useful indicators of task intrusion, reflecting the drivers' perceptions of road performance requirements and experiences of workload. The composite attentional measure, viewing ratio, exhibited a significant and large dependency on the difficulty of the driving task. The other attention variables, dwell time and look frequency, exhibited similar trends. In addition, dwell time was marginally affected by the difficulty of the auxiliary task.

The results of the attentional response data suggest that auxiliary in-vehicle displays could draw a significant proportion of the drivers' visual attention under dual task conditions. Under certain conditions, more than 50% of the time was spent looking inside the vehicle. It is also important to note that subjects directed significantly more attention towards the auxiliary display when performing a cognitive task than under the control condition. This suggests that, under certain circumstances, auxiliary visual displays can potentially cause drivers to pay insufficient attention to the road. Diversion of visual attention from the road to auxiliary displays could contribute towards increased levels of driver inattention leading to increased risk of unwitting lane exceedence or of failure to detect obstacles in the road environment. In these experiments, it was not possible to introduce unexpected events to determine how such lapses of attention could affect obstacle avoidance performance. Such studies are a logical extension of this work.

As discussed in Experiment Two, variables of attention such as viewing ratio, look frequency, and dwell time may each have unique properties that reflect the driver's subjective strategy in resolving conflicting data acquisition and scheduling demands. The interrelationships between look frequency and dwell time, the factors affecting their interdependence and their differential effect on driving warrant further investigation. Useful insight into the attention behaviour of drivers can be gained from further studies designed especially to examine eye movement behaviour under manipulations of display legibility, driving load, etc. The present results generally support the relevance of current models of monitoring behaviour, but suggest that these models need to reflect more accurately the priority given to driving. These models should be extended to incorporate speed/accuracy tradeoff decisions which occur near the limits of human attentional capacity to account properly for the complexity of time-sharing in driving. We suggest that elements from economic theory, such as subjective and objective substitution rate, might be relevant to a further extension of these models. The Supervisory Driver Model provides a somewhat different approach which appears to incorporate many of the elements already discussed. However, the accuracy of this model might be improved if the model had provisions for the performance of non-tracking tasks to the extent that such auxiliary tasks might interfere with driving.

Importantly, the intermediate variables of attention were more sensitive to experimental manipulations than the primary driving variables. It was suggested that shifts in attention were driven primarily by changes in the attentional demands of driving. Primary task measures were less sensitive because drivers were able to allocate sufficient resources to driving to maintain performance within narrow bands (under normal conditions). It would be of interest, however, to investigate other driving scenarios such as obstacle avoidance to determine how performance on these tasks may be affected by auxiliary displays.

The implication behind the model of Zaidel et al., shown in Figure 1, is that attention and performance in driving are highly interdependent. Indeed, the results of these experiments support this view. Both attention and performance were affected by driving demand, as predicted by the model. This interdependence was described in Experiment One as a form of driver adaptation - drivers modified their attention strategies on the basis of driving demand, but their objective was to maintain a constant level of performance. Experiments Two and Three corroborated the notion that drivers are adept at altering their behaviour to compensate for changes in the perceptual/mediational/motor demands imposed by competing tasks to exhibit reasonably stable levels of driving performance. Comparisons of performance while looking outside the vehicle with performance while looking inside were found to be consistent with the notion of driver adaptation. Looking inside the vehicle was associated with better performance because this condition was most likely to be observed when the subject considered the vehicle to be under control (e.g., its projected path over the next few moments was judged to permit safe sampling from the auxiliary display).

However, the data also demonstrate that despite the presence of adaptation mechanisms, driving performance was adversely affected in the presence of an auxiliary task, as discussed earlier.

This study points to the need for further investigations and suggests a number of directions for future research. Factors affecting drivers' capabilities and limitations under conditions of dual task driving need to be fully explored and understood so that ergonomics principles and guidelines for the design of auxiliary displays can be further developed. For example, it has been pointed out that display factors such as legibility may be important. The extent to which such factors affect driving is an important area of investigation. A related question concerns the quantification of the information content of an auxiliary display as it may relate to drivers' performance. The issue of display modality was raised and further investigations are required to determine any benefits that such technology might offer to driver interface effectiveness. Similarly, the use of HUD's needs to be carefully evaluated to ascertain that they are able to reduce the potential for distraction and do not introduce additional problems to the driver.

One limitation inherent in the methodology of this study concerns the fact that the performance measures that were obtained represented data that had been integrated over a finite period of time, rather than instantaneous responses to specific events. For example, TLC measures were obtained for each curve type in each trial. But within each curve type, the measure represented the median of some 200 samples. Hence, the data may not necessarily reflect extreme values that are of interest in assessing the effects of auxiliary task intrusion on driving.

Lags in vehicle response did result in some carryover of effect from one road segment to the next. For example, despite the presence of straight segments separating curves and transition lengths at the start of each curve, measures such as lane position, velocity, and headway did reflect, to some extent, events or conditions which prevailed during the previous curve. This was evident in some of the trial tracings (see Figure 4.3.1.2.1) The consequence of the carryover effect is to increased the variance in the data. While this problem is difficult to overcome, it does not detract from the validity of the findings.

The nature of the driving task precluded estimating the effect on the readiness of drivers to respond to unexpected occurrences in the roadway while attending to auxiliary tasks. A related concern is the effects on drivers' judgements and resolution of traffic conflicts. While this is an important issue for road safety, it was beyond the scope of the present experiment.

The subjects who participated in this experiment were young students who could be considered to be technology-literate. Further experimentation is required to assess the impact of auxiliary displays on other segments of the driving population, such as the elderly.

These and similar studies should also be repeated under field conditions and in real traffic in attempts to replicate the results.

As a final note, the need to establish links between experimental measures of driving (whether they are collected in the laboratory, simulator or field) and aggregate measures of road safety is becoming urgent. This formidable task must be faced in order to ensure that guidelines and regulations for the design and use of auxiliary displays are based on demonstrated safety and other benefits.

8. REFERENCES

Allen, R.W., and Weir, D.H., 1984. Analysis of Man-In-The-Loop Performance Measurement Technology for Crash Avoidance Research. NHTSA Report No., DOT HS 806 718.

Allen, T.M., Lunenfeld, H., and Alexander, G.J., 1971. Driver Information Needs. *Highway Research Record*, HRR 366 - Traffic Control and Driver Information, 102-114.

Antin, J.F., Dingus, T.A., Hulse, M.C., Wierwille, W.W., 1986a. Human Factors Test and Evaluation of an Automobile Moving-Map Navigation System, Part I: Attentional Demand Requirements. General Motors Research Laboratories, GM Technical Center, Warren, Michigan.

Antin, J.F., Dingus, T.A., Hulse, M.C., Wierwille, W.W., 1986b. Human Factors Test and Evaluation of an Automobile Moving-Map Navigation System, Part II: Methodology Issues - Effectiveness, Efficiency, and Strategy. General Motors Research Laboratories, GM Technical Center, Warren, Michigan.

Armstrong, B.D., 1977. The Need for Route Guidance. Transport and Road Research Lab., TRRL-Supplementary-330, NTIS-PB-277 506.

Avolio, B.J., Kroeck, K.G., and Panek, P.E., 1985. Individual Differences in Information-Processing Ability as a Predictor of Motor Vehicle Accidents. *Human Factors*, 27(5), 577-587.

Baxter, J., and Harrison, J.Y., 1979. A Nonlinear Model Describing Driver Behaviour on Straight Roads. *Human Factors, 21(1), 87-97.*

Bishop, R.W., Calvin, R.M., and McPherson, K., 1975. *Driving: A Task Analysis Approach*. Rand McNally & Co.

Blaauw, G.J., 1982. Driving Experience and Task Demands in Simulator and Instrumented Car: A Validation Study. *Human Factors*, 24(4), 473-486.

Blaauw, G.J., 1984. Car Driving as a Supervisory Control Task. Institute for Perception TNO, Soesterberg - the Netherlands.

Blaauw, G.J., Godthelp, J. and Moraal, J., 1977. Driver's Lateral Control Strategy as Affected by Task Demands and Driving Experience, SAE, 770876.

Blaauw, G.J., Godthelp, J., and Milgram, P., 1984. Optimal Control Model Applications and Field Measurements With Respect to Car Driving, *Vehicle System Dynamics*, 13, 93-111.

Boadle, J., 1976. Vigilance and Simulated Night Driving. *Ergonomics*, 19(2), 217-225.

Brown, I.D., 1965. A Comparison of Two Subsidiary Tasks Used to Measure Fatigue in Car Drivers. *Ergonomics*, 8, 467-473.

Brown, I.D., and Poulton, E.C., 1961. Measuring the Spare 'Mental Capacity' of Car Drivers By a Subsidiary Task. *Ergonomics*, 4(1), 35-40.

Brown, I.D., Simmonds, D.C.V., and Tickner, A.H., 1967. Measurement of Control Skills, Vigilance, and Performance on a Subsidiary Task During 12 Hours of Car Driving. *Ergonomics*, 10(6), 665-673.

Brown, I.D., Tickner, A.H., and Simmonds, D.V.C., 1969. Interference Between Concurrent Tasks of Driving and Telephoning. *Journal of Applied Psychology*, 53(4), 419-424.

Brown, R.J., Edington, M.A., and Todes, D.S., 1986. Potential Benefits of Route Guidance Systems in a Metropolitan Area. *IEE Second International Conference on Road Traffic Control*, Conference Publication 260, 10-14.

Carbonell, J.R., 1966. A Queueing Model for Many-Instrument Visual Sampling. *IEEE Transactions on HumanFactors in Electronics*. HFE-7, pp157-164.

Ceder, A., 1977. Drivers' Eye Movements as Related to Attention in Simulated Traffic Flow Conditions. *Human Factors*, 19(6), 571-581.

Cohen, A.S., 1978. Eye Movements Behaviour While Driving a Car: A Review. US ARI Report TR-78-T54.

Cohen, A.S., and Studach, H., 1977. Eye Movements While Driving Cars Around Curves. *Perceptual and Motor Skills*, 44, 683-689.

Colbourn, C.J., Brown, I.D., and Copeman, A.K., 1978. Drivers' Judgements of Safe Distances in Vehicle Following. *Human Factors*, 20(1), 1-11.

Dellis, E., 1988. Automotive Head-Up Displays: Just Around the Corner. *Automotive Engineering*, February, 107-110.

Derrick, W.L., McCloy, T.M., 1984. An Empirical Demonstration of Multiple Resources. *Proc. Human Factors Society 28th Meeting*.

Dewar, R.E., 1984. Ergonomics in Highway Transportation. *Proceedings of the 1984 International Conference on Occupational Ergonomics*, Vol. 1, Human factors Association of Canada.

Dewar, R.E., 1988. In-Vehicle Information and Driver Overload. *International Journal of Vehicle Design*, 9(4/5), pp 557-564.

Dewar, R.E., and Lim, C.S., 1987. Cognitive Ability, Perceptual Style, and Traffic Accidents. Road Safety and Motor Vehicle Regulation Directorate, Transport Canada.

Dingus, T.A, Antin, J.F., and Wierwille, W.W., 1988. Human Factors Issues Associated with In-Car Navigation System Usage. *Proc. Human Factors Society 32nd Annual Meeting*, Anaheim, 1448-1452.

Dobbins, D.A., Tiedemann, J.G. and Skordahl, D.M., 1963. Vigilance Under Highway Driving Conditions. *Perceptual and Motor Skills,* 16, 38.

Donges, E., 1978. A Two-Level Model of Driver Steering Behaviour. *Human Factors*, 20(6), 691-707.

Drory, A., 1985. Effects of Rest and Secondary Task on Simulated Truck-Driving Task Performance. *Human Factors*, 27(2), 201-207.

Eriksen, B.A., Eriksen, C.W., and Hoffman, J.E., 1986. Recognition Memory and Attention Selection: Serial Scanning is not Enough. *Journal of Experimental Psychology: Human Perception and Performance*, 12(4), 476-483.

Fagerstrom, K.-O., and Lisper, H.-O., 1977. Effects of Listening to Car Radio, Experience, and Personality of the Driver on Subsidiary Reaction Time and Heart Rate in a Long-Term Driving Task. In Mackie, R.R., **Vigilance; Theory, Operational Performance and Physiological Correlates**. NATO Conference Series, Plenum Press, 73-85.

Fisk, A.D., Derrick, W.L., and Schneider, W., 1983. The Assessment of Workload: Dual Task Methodology. *Proc. Human Factors Society 27th Meeting,* 229-233.

Fowkes, M., 1984. Presenting Information to the Driver, *Displays*, October.

Frank, L.H., Casali, J.G., and Wierwille, W.W., 1987. Effects of Visual Display and Motion System Delays on Operator Performance and Uneasiness in a Driving Simulator. *Proc. Human Factors Society 31st Meeting*,492-496.

French, R.L., 1986. In-Vehicle Route Guidance in the United States: 1910-1985. *IEE Second International Conference on Road Traffic Control*, Conference Publication 260, 6-9.

Galer, M.D., 1984. The Application of Ergonomics in the Design of Automobile Displays, *Displays*, October, 224-228.

Galer, M.D., and Simmonds, G., 1984. Ergonomic Aspects of Electronic Instrumentation: A Guide for Designers, SAE, SP-576.

Garber, N.J., and Gadirau, R., 1988. Speed Variance and its Influence on Accidents, AAA Foundation for Traffic Safety.

Garrot, W.R., Wilson, D.L., and Scott, R.A., 1982. Closed Loop Automobile Maneuvers Using Preview-Predictor Models. *SAE Paper Series* 820305.

Godthelp, H., 1984. Studies on Human Vehicle Control, Institute for Perception TNO, Soesterberg - the Netherlands.

Godthelp, H., 1986. Vehicle Control During Curve Driving. *Human Factors*, 28(2), 211-221.

Godthelp, H., Blaauw, G.J., and Milgram, P., 1984. Supervisory Behaviour in Automobile Driving: New Approaches in Modeling Vehicle Control. *XXth FISITA Congress*, SAE, P-143.

Godthelp, H., Milgram, P., and Blaauw, G.J., 1984. The Development of a Time-Related Measure to Describe Driving Strategy. *Human Factors*, 26(3), 257-268.

Goettl, B.P., 1985. The Interfering Effects of Processing Code on Visual Memory. *Proc. Human Factors Society 29th Meeting.*

Gopher, D., Brickner, M., and Navon, D., 1982. Different Difficulty Manipulations Interact Differently With Task Emphasis: Evidence for Multiple Resources. *Journal of Experimental Psychology: Human Perception and Performance*, 8(1), 146-157.

Grant, P.R., 1986. Motion Characteristics of the UTIAS Flight Research Simulator Motion-Base. UTIAS Technical Note No. 261, University of Toronto Institute for Aerospace Studies.

Hagen, R.E., 1975. Sex Differences in Driving Performance. *Human Factors*, 17(2), 165-171.

Hakkinen, S., 1976. Traffic Accidents and Psychomotor Test Performance: A Follow-Up Study. *Modern Problems of Pharmacopsychiatry*, V11, pp51-56.

Hall, H.H., 1986. Alternate Approaches to Automotive Navigation. SAE P-183, *Proceedings of the International Congress on Transportation Electronics*.

Harms, L., 1986. Drivers' Attentional Responses to Environmental Variations: A Dual-Task Real Traffic Study. In Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P. and Taylor, S.P., **Vision In Vehicles**, Elsevier Science Publishers B.V. (North-Holland).

Harris, W.J., and Bridges, G.S., 1989. Proceedings of a Workshop on Intelligent Vehicle/Highway Systems by Mobility 2000. Texas Transportation Institute, The Texas A&M University System.

Hart, S.G., and Sheridan, T.B., 1984. Pilot Workload, Performance, and Aircraft Control Automation. *AGARD Conference Proceedings*, No. 371, Human Factors Considerations in High Performance Aircraft.

Hart, S.G., and Staveland, L.E., 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In P.A. Hancock and N. Meshkati (Eds), **Human Mental Workload**, North-Holland.

Hartmann, E., 1970. Driver Vision Requirements. International Automobile Safety Conference, SAE.

Heimstra, N.W., 1970. The Effects of 'Stress Fatigue' on Performance in a Simulated Driving Situation. *Ergonomics*, 13(2), 209-218.

Hicks, T.G., and Wierwille, W.W., 1979. Comparison of Five Mental Workload Assessment Procedures in a Moving-Base Driving Simulator. *Human Factors*, 21(2), 129-143.

Hills, B.L., 1980. Vision, Visibility, and Perception in Driving. *Perception*, 9, 183-216.

Hoffman, E.R., and Joubert, P.N., 1966. The Effect of Changes in Some Vehicle Handling Variables on Driver Steering Performance. *Human Factors*, 8, 245-263.

Hucho, W.-H., 1984. Trends in the Development of Vehicle Instruments, *International Journal of Vehicle Design*, 5(3), pp 291-304.

Hulbert, S., 1984. The Driving Task. In Peters, G.A. and Peters, B.J., **Automotive Engineering and Litigation, Volume I**, Garland Law Publishing.

Iavecchia, J.H., Iavecchia, H.P., and Illiana, R., 1988. Eye Accommodation to Head-Up Virtual Images, *Human Factors*, 30(6), 689-702.

Jeffery, D.J., 1981. Ways and Means for Improving Driver Route Guidance. Transport and Road Research Lab., TRRL Report 1016.

Jeffrey, D.J., Russam, K., and Robertson, D.I., 1987. Electronic Route Guidance by AUTOGUIDE: The Research Background, *Traffic Engineering and Control*, 28(10), 525-529.

Johnston, A.W., and Cole, B.L., 1976. Investigations of Distraction by Irrelevant Information. *Australian Road Research*, 6(3), 3-23.

Kahneman, D., and Ben-Ishai, R., 1973. Relation of a Test of Attention to Road Accidents. *Journal of Applied Psychology*, 58(1), 113-115.

Kaluger, N.A., and Smith Jr., G.L., 1970. Driver Eye-Movement Patterns Under Conditions of Prolonged Driving and Sleep Deprivation. *Highway Research Record*, No. 336 - Night Visibility and Driver Behaviour.

Kantowitz, B.H., 1985. Channels and Stages in Human Information Processing: A limited Analysis of Theory and Methodology. *J. Mathematical Psychology*, 29, 135-174.

Kennedy, R.S., Berbaum, K.S., Lilienthal, M.G., Dunlap, W.P., and Mulligan, B.E., 1987. Guidelines for Alleviation of Simulator Sickness Symptomatology. Naval Training Systems Centre, NAVTRASYSCEN TR-87-007.

Kessel, K.L., 1986. Advanced Automation (AA) in Tactical Aircraft May Have Negative Effects on Pilot Performance. *Proc. IEEE Conf. on Systems, Man and Cybernetics*, CH2364-8.

Knoernschild, G.F., 1986. Global Positioning System for Vehicle Navigation and Position Reporting. SAE P-183, *Proceedings of the International Congress on Transportation Electronics*.

Kramer, U., and Rohr, G., 1982. A Model of Driver Behaviour. *Ergonomics*, 25(10), 891-907.

Kramer, U., and Neculau, M., 1986. Driver's Display, Eye-Movements, and Steering Behaviour: The Visual Basis of Car Driving. In Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P. and Taylor, S.P., **Vision In Vehicles**, Elsevier Science Publishers B.V. (North-Holland).

Kroll, C.V., 1971. Preview-Predictor Model of Driver Behaviour in Emergency Situations. *Highway Research Record*, 364, 16-26.

Laurell, H., and Lisper, H.-O., 1978. A Validation of Subsidiary Reaction Time Against Detection of Roadside Obstacles During Prolonged Driving. *Ergonomics*, 21(2), 81-88.

Laycock, J., 1979. The Measurement and Analysis of Eye Movements. In Clare, J.N. and Sinclair, M.A., (Eds), **Search and the Human Observer**, Taylor and Francis, London.

Lim, C.S., and Dewar, R.E., 1988. Field Dependence and Traffic Accidents Among Bus Drivers. *Proceedings of the Annual Conference of the Human Factors of Canada*.

Lisper, H.O., Laurell, H., and Stening, G., 1973. Effects of Experience of the Driver on Heart-rate, Respiration-rate, and Subsidiary Reaction Time in a Three Hours Continuous Driving Task. *Ergonomics*, 16(4), 501-506.

Lisper, H.O., Eriksson, B., Fagerstrom, K.-O., and Lindholm, J., 1979. _Diurnal Variation in Subsidiary Reaction Time in a Long-Term Driving Task. *Accident Analysis and Prevention*, 11, 1-5.

Lisper, H.O., Laurell, H., and Loon, J. van, 1986. Relation Between Time to Falling Asleep Behind the Wheel on a Closed Track and Changes in Subsidiary Reaction Time During Prolonged Driving on a Motorway. *Ergonomics*, 29(3), 445-453.

Liu, Y., and Wickens, C.D., 1987. The Effect of Processing Code, Resource Modality and Task Difficulty on Dual Task Performance and Subjective Workload in a Manual System. *Proc. Human Factors Society 31st Meeting.*

Macdonald, W.A., and Hoffmann, E.R., 1980. Review of Relationships Between Steering Wheel Reversal Rate and Driving Task Demand. *Human Factors*, 22(6), 733-739.

McDonald, L.B., and Ellis, N.C., 1975. Driver Work Load for Various Turn Radii and Speeds. *Transportation Research Record,* 530.

McGuire, F.L., 1976. Personality Factors in Highway Accidents. *Human Factors*, 18(5), 433-441.

McKena, F.P., Duncan, J., and Brown, I.D., 1986. Cognitive Abilities and Safety on the Road: A Re-examination of Individual Differences in Dichotic Listening and Search for Embedded Figures. *Ergonomics*, 29(5), 649-663.

McKnight, A,J., and Hundt, A.G., 1971. Driver Education Task Analysis: Instructional Objectives. *HumRRO Safety Series*, Human Resources Research Organization.

McLean, J.R., and Hoffmann, E.R., 1973. The Effects of Restricted Preview on Driver Steering Control and Performance. *Human Factors*, 15(4), 421-430.

McRuer, D.T., Allen, W.R., Weir, D.H., and Klein, R.H., 1977. New Results in Driver Steering Control Models. *Human Factors*, 19(4), 381-397.

Miller, H.R., Allen, R.W., and Stein, A.C., 1983. Driver Factors, Simulators and Other Instrumented Measurement Approaches. *SAE Technical Paper Series*, No. 830563.

Ministry of Transportation and Communications (Ontario), 1985. Geometric Design Standards for Ontario Highways. MTC Highway Design Office.

Moray, N., 1986. Monitoring Behaviour and Supervisory Control. In Boff, K.R., Kaufman, L., and Thomas, J.P., (Eds.) **Handbook of Perception and Human Performance, Volume II Cognitive Processes and Performance**. John Wiley and Sons.

Moray, N. and Smiley, A., 1984. Human Stress in Vehicle Operation. Transportation Development Centre, Transport Canada.

Mourant, R.R., and Rockwell, T.H., 1972. Strategies of Visual Search by Novice and Experienced Drivers. *Human Factors*, 14(4), 325-335.

Mourant, R.R., and Grimson, C.G., 1977. Predictive Head-Movements During Automobile Mirror-Sampling. *Perceptual and Motor Skills*, 44, 283-286.

Navon, D., and Gopher, D., 1979. On the Economy of the Human Processing System. *Psychological Review*, 86(3), 214-233.

Navon, D., and Gopher, D., 1980. Task Difficulty, Resources, and Dual-Task Performance. In R. Nickerson and R. Pew (Eds), **Attention and Performance VIII**, Hillsdale, NJ: Erlbaum.

Neculau, M., Sepher, M., and Kramer, U., 1986. Saccadic Eye-Movements and Work Load of the Car Driver. In Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P. and Taylor, S.P., **Vision In Vehicles**, Elsevier Science Publishers B.V. (North-Holland).

Norman, D.A., and Bobrow, D.G., 1975. On Data-Limited and Resource-Limited Processes. *Cognitive Psychology*, 7, 44-64.

Noy, Y.I., 1987. Theoretical Review of the Secondary Task Methodology for Evaluating Intelligent Automobile Displays. *Proceedings, 31st Annual Meeting of the Human Factors Society*, New York.

Olson, J.B., 1987. Case Study: The First Automotive-Display Touch Panel. *Information Display*, 3(1), 12-16.

Organization for Economic Co-operation and Development (OECD), 1987. Driver Information and Guidance Systems Using In-Car Communications. Road Transport Research Programme, Final Report.

Quenault, S.W., 1968. Task Capability While Driving. Road Research Laboratory, RRL Report LR166, Crowthorne, Berkshire.

Reid, L.D., 1983. A Survey of Recent Driver Steering Behaviour Models Suited to Accident Studies. *Accident Analysis and Prevention*, 15(1), 23-40.

Riemersma, J.B.J., Sanders, A.F., Wildervanck, C., and Gaillard, A.W., 1977. Performance Decrement During Prolonged Night Driving. In Mackie, R.R., **Vigilance; Theory, Operational Performance and Physiological Correlates**. NATO Conference Series, Plenum Press.

Robinson, G.H., Erickson, D.J., Thurston, G.L., and Clark, R.L., 1972. Visual Search by Automobile Drivers. *Human Factors*, 14(4), 315-323.

Rockwell, T., 1972. Skills, Judgment and Information Acquisition in Driving. In Forbes, T.W. (Ed), **Human Factors in Highway Traffic Safety Research**. Wiley Interscience.

Roscoe, S.N., 1986. Designed for Disaster. *Human Factors Bulletin*, 29(6), 1-2.

Rouse W.B., and Cody, W.J., 1986. Function Allocation in Manned System Design. *Proc. IEEE Conf. on Systems, Man and Cybernetics*, CH2364-8.

Sanders, A.F., and Noble, M.E., 1975. Visual Search and Tracking as Single and Dual Tasks. Institute for Perception TNO, Report IZF 1975-C13, Soesterberg, the Netherlands.

Schaeffer, M.S., and Campbell, J.L., 1988. Vertical Disparity in Advanced Automobile Displays. *Proc. Human Factors Society 32nd Annual Meeting*, Anaheim.

Schiff, W., and Detwiler, M.L., 1979. Information Used in Judging Impending Collision. *Perception*, 8, 647-658.

Senders, J.W., Elkind, J.E., Grignetti, M.C., and Smallwood, R.P., 1964. **An Investigation of the Visual Sampling Behaviour of Human Observers**. NASA-CR-434, Bolt, Beranek & Newman, Cambridge.

Senders, J.W., Kristofferson, A.B., Levison, W.H., Dietrich, C.W., and Ward, J.L., 1967. The Attentional Demands of Automobile Driving. *Highway Research Record*, 195.

Shinar, D., McDowell, E.D., and Rockwell, T.H., 1977. Eye Movements in Curve Negotiation. *Human Factors*, 19(1), 63-71.

Snyder, H.L., and Bogle, R.H. 1984. Electronic Displays: Their Strengths and Weaknesses for Advanced High Performance Aircraft. *AGARD Conference Proceedings*, No. 371, Human Factors Considerations in High Performance Aircraft.

Snyder, H.L., and Monty, R.W., 1986. A Methodology for Road Evaluation of Automobile Displays. In Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P. and Taylor, S.P., **Vision In Vehicles**, Elsevier Science Publishers B.V. (North-Holland).

Staplin, L.K., Breton, M.E., Haimo, S.F., Farber, E., Byrnes, A.M., in press. Age-Related Diminishing Capabilities and Driver Performance. U.S. Federal Highway Administration.

Stein, A.C., Parseghian, Z., and Allen, R.W., 1987. A Simulator Study of the Safety Implications of Cellular Mobile Phone Use. *31st Annual Proceedings American Association for Automotive Medicine*, 181-200.

Stephens, B.W., and Michaels, R.M., 1964. Timesharing Between Two Driving Tasks: Simulated Steering and Recognition of Road Signs. *Public Roads*, 33(5), 81-88.

Sternberg, S., 1969. The Discovery of Processing Stages: Extension of Donder's Method. *Acta Psychologica*, 30, 276-315.

Sussman, E.D., Bishop, H., Madnick, B., and Walter, R., 1985. Driver Inattention and Highway Safety. *Transportation Research Record*, 1047, 40-48.

Swift, D.W., and Freeman, M.H., 1986. The Application of Head-Up Displays to Cars. In Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P. and Taylor, S.P., **Vision In Vehicles**, Elsevier Science Publishers B.V. (North-Holland).

Thoone, M.L.G., Driessen, L.M.H.E., Hermus, C.A.C.M., and Volk, K. van der, 1987. The Car Information and Navigation System CARIN and the USe of Compact Disc Interactive, *SAE* 870139.

Thorndyke, P.W., and Stasz, C., 1980. Individual Differences in Procedures for Knowledge Acquisition From Maps. *Cognitive Psychology*, 12, 137-175.

Tomkewitsch, R. von, 1986. ALI-SCOUT - A Universal Guidance and Information System for Road Traffic. *IEE Second International Conference on Road Traffic Control*, Conference Publication 260, 22-25.

Treat, J.R., Tumbas, N.S., McDonald, S.T., Shinar, D., Hume, R.D., Mayer, R.E., Stansifer, R.L., and Castellan, N.J., 1979. Tri-Level Study of the Causes of Traffic Accidents: Final Report, Volumes I and II. U.S. DOT HS-805-086, (NTIS PB 80-121064).

Treisman, A., 1982. Perceptual Grouping and Attention in Visual Search for Features and for Objects. *Journal of Experimental Psychology: Human Perception and Performance,* 8(2), 194-214.

Treisman, A., 1986. Features and Objects in Visual Processing. *Scientific American*, November, 114-122.

Tsang, P., Hart, S.G., and Vidulich, M.A., 1986. The Effects of Display-Control I/O, Compatibility, and Integrality on Dual-Task Performance and Subjective Workload. *AGARD Conferences Proceedings* - Information Management and Decision Making in Advanced Airborne Weapon Systems.

Tsunoda, M., Ishikawa, S., Itoh, T., and Iwabuchi, M., 1986. Navigation Systems for Passenger Cars, SAE P-183, *Proceedings of the International Congress on Transportation Electronics*.

Tynan, P.D., and Sekuler, R., 1982. Motion Processing in Peripheral Vision: Reaction Time and Perceived Velocity. *Vision Research*, 22, 61-68.

Wetherell, A., 1981. The Efficacy of Some Auditory-Vocal Subsidiary Tasks as Measures of the Mental Load on Male and Female Drivers. *Ergonomics*, 24(3), 197-214.

Wickens, C.D., 1980. The Structure of Attentional Resources. In R. Nickerson and R. Pew (Eds), **Attention and Performance VIII**, Hillsdale, NJ: Erlbaum.

Wickens, C.D., 1984. Processing Resources in Attention. In Parasuraman, R., and Davies, D.R., (Eds), **Varieties of Attention**, Academic Press.

Wickens, C.D., Sandry, D.L., and Vidulich, M., 1983. Compatibility and Resource Competition Between Modalities of Input, Central Processing, and Output. *Human Factors*, 25(2), 227-248.

Wickens, C.D., Hyman, F., Dellinger, J., Taylor, H., and Meador, M., 1986. The Sternberg Memory Search Task As an Index of Pilot Workload. *Ergonomics*, 29(11), 1371-1383.

Wickens, C.D., Yeh, Y.-Y., 1986. A Multiple Resource Model of Workload Prediction and Assessment. *Proc. IEEE Conf. on Systems, Man and Cybernetics,* CH2364-8.

Wiener, E.L., and Curry, R.E., 1980. Flight-Deck Automation: Promises and Problems. *Ergonomics*, 23(10), 995-1011.

Wierwille, W.W., 1975. Driving Simulator Design for Realistic Handling. In Sachs, H.K. (Ed.), *Proceedings of the Third International Conference on Vehicle System Dynamics,* Swets and Zeitlinger, Amsterdam, 186-199.

Wierwille, W.W., Gutmann, J.C., Hicks, T.G., and Muto, W.H., 1977. Secondary Task Measurement of Workload as a Function of Simulated Vehicle Dynamics and Driving Conditions. *Human Factors,* 19(6), 557-565.

Wierwille, W.W., and Gutmann, J.C., 1978. Comparison of Primary and Secondary Task Measures as a Function of Simulated Vehicle Dynamics and Driving Conditions. *Human Factors*, 20(2), 233-244.

Wierwille, W.W., Hulse, M.C., Fischer, T.J., Dingus, T.A., 1988. Effects of Variations in Driving Task Attentional Demand on In-Car Navigation System Usage. General Motors Research Laboratories, GM Technical Center, Warren, Michigan.

Wilhelm, R.V. Jr., 1987. The Automotive Instrumentation Explosion: Growth, Challenges, and Partnerships. Delco Electronics Corporation. Keynote address presented at the *1987 International Symposium of the Society for Information Display.*

Witkin, H.A., Oltman, P.K., Raskin, E., and Karp, S.A., 1971. A Manual for the Embedded Figures Tests. Consulting Psychologists Press, Inc., California.

Zaidel, D.M., Paarlberg, W.T., and Shinar, D., 1978. Driver Performance and Individual Differences in Attention and Information Processing, Volume I: Driver Inattention. Institute for Research in Public Safety, DOT-HS-803 793.

Zeitlin, L.R., and Finkelman, J.M., 1975. Research Note: Subsidiary Task Techniques of Digit Generation and Digit Recall as Indirect Measures of Operator Loading. *Human Factors*, 17(2), 218-220.

Zwahlen, H.T., 1982. Driver Eye Scanning on Curves and on Straight Sections on Rural Highways. Proc. Human Factors Society 26th Meeting.

Zwahlen, H.T., 1985. Driver Eye Scanning, The Information Acquisition Process and Sophisticated In-Vehicle Information Displays and Controls. *Proc. Ninth Congress of the International Ergonomics Association,* 508-510.

Zwahlen, H.T., and Balasubramanian, K.N., 1974. A Theoretical and Experimental Investigation of Automobile Path Deviations When Driver Steers With No Visual Input. *Transportation Research Record*, 520, 25-37.

Zwahlen, H.T., and DeBald, D.P., 1986. Safety Aspects of Sophisticated In-Vehicle Information Displays and Controls. *Proc. Human Factors Society 30th Meeting,* 256-260.

Zwahlen, H.T., Adams, C.C., and Schwatz, P.J., 1988. Safety Aspects of Cellular Telephones in Automobiles. Paper prepared for the Int'l Symposium on Automotive Technology and Automation, Florence, Italy.

9. APPENDIX A - Data Tables

Contents:

Data are provided in columnar format for different combinations of Group, Treatment (TRT) and Curve Type. Blank cells for levels of the independent variable indicates that the data were collapsed over all levels of the variable. For each unique combination, the first row of data presents means and the second row presents the corresponding standard deviations.

The first set of tables provide driving performance data; the second set provide attention data and auxiliary task performance.

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
			3.04	0.23	55.32	0.01	0.9

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
		130 m	2.53	0.25	56.06	0.02	0.94
		250 m	3.02	0.23	55.48	0.01	0.88
		340 m	3.24	0.22	54.65	0.01	0.91
		Straight	3.68	0.24	54.87	0.01	0.87

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
	1		2.92	0.24	54.32	0.01	0.94
	2		2.9	0.25	54.47	0.02	0.89
	3		2.91	0.25	55.68	0.02	0.98
	4		2.84	0.25	56.45	0.02	0.91
	Control		3.08	0.23	57.79	0.01	0.91
	Baseline		3.57	0.19	53.23		0.79

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
	1	130 m	2.47	0.25	53.88	0.02	0.99
	1	250 m	2.92	0.23	54.9	0.01	0.96
	1	340 m	3.08	0.22	54.08	0.01	0.92
	1	Straight	3.49	0.25	54.53	0.01	0.86
	2	130 m	2.47	0.26	55.4	0.02	0.92
	2	250 m	2.9	0.23	54.12	0.02	0.91
	2	340 m	3.06	0.24	54.02	0.02	0.89
	2	Straight	3.41	0.28	54.19	0.01	0.81
	3	130 m	2.54	0.26	55.54	0.02	0.94
	3	250 m	2.9	0.24	56.26	0.02	0.91
	3	340 m	2.98	0.24	55.47	0.01	1.02
	3	Straight	3.55	0.25	55.22	0.01	1.08
	4	130 m	2.43	0.27	57.52	0.03	0.94
	4	250 m	2.77	0.26	56.82	0.02	0.85
	4	340 m	3	0.23	55.23	0.02	0.97
	4	Straight	3.45	0.25	56.04	0.01	0.88
	Control	130 m	2.53	0.25	58.56	0.03	0.95
	Control	250 m	3.1	0.23	58.21	0.01	0.9
	Control	340 m	3.26	0.21	57.42	0.01	0.92
	Control	Straight	3.76	0.23	56.15	0.01	0.84
.	Baseline	130 m	2.75	0.22	55.47	0.01	0.9
.	Baseline	250 m	3.5	0.18	52.6		0.74
.	Baseline	340 m	4.04	0.17	51.69		0.75
.	Baseline	Straight	4.39	0.19	53.1		0.75

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
B			3.04	0.23	53.6	0.01	0.87
M			2.96	0.24	53.03	0.02	0.98
P			3.1	0.23	59.34	0.02	0.86

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
B		130 m	2.57	0.24	53.78	0.02	0.95
B		250 m	2.99	0.22	53.85	0.01	0.82
B		340 m	3.3	0.2	53.26	0.01	0.87
B		Straight	3.57	0.24	53.43		0.83
M		130 m	2.48	0.26	53.84	0.02	0.98
M		250 m	2.9	0.24	53.12	0.02	0.96
M		340 m	3.14	0.23	52.5	0.01	1.02
M		Straight	3.69	0.25	52.32	0.01	0.94
P		130 m	2.55	0.25	60.56	0.02	0.9
P		250 m	3.15	0.22	59.49	0.02	0.86
P		340 m	3.27	0.22	58.2	0.02	0.85
P		Straight	3.76	0.23	58.87	0.01	0.84

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
B	1		2.81	0.23	52.12	0.01	0.94
B	2		3.03	0.23	50.38	0.01	0.87
B	3		2.84	0.25	53.11	0.01	0.92
B	4		2.79	0.24	53.35	0.01	0.89
B	Control		3.01	0.23	60	0.02	0.82
.	Baseline		3.77	0.17	52.65		0.8
M	1		2.89	0.25	52.72	0.02	0.98
M	2		2.77	0.26	57.82	0.02	1.02
M	3		2.87	0.25	53.61	0.02	1.1
M	4		2.73	0.27	52.78	0.03	0.99
M	Control		3.11	0.23	51.77	0.01	0.96
.	Baseline		3.42	0.2	52.5		0.83
P	1		3.05	0.23	58.11	0.01	0.9
P	2		2.9	0.25	58.2	0.03	0.8
P	3		3.02	0.25	60.32	0.01	0.9
P	4		2.99	0.25	63.24	0.03	0.86
P	Control		3.12	0.23	61.6	0.01	0.96
.	Baseline		3.51	0.19	54.55		0.75

GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL
B	1	130 m	2.44	0.23	50.65	0.01	0.89
B	1	250 m	2.83	0.23	53.57	0.02	1.03
B	1	340 m	3.04	0.22	52.29	0.01	0.96
B	1	Straight	3.09	0.27	51.82	0.01	0.85
B	2	130 m	2.67	0.24	51.12	0.01	0.94
B	2	250 m	2.86	0.23	49.42	0.01	0.81
B	2	340 m	3.34	0.21	50.48	0.02	0.9
B	2	Straight	3.46	0.27	50.62		0.8
B	3	130 m	2.61	0.28	51.58	0.02	0.9
B	3	250 m	2.78	0.24	54.02	0.01	0.84
B	3	340 m	2.91	0.24	53.37	0.01	0.97
B	3	Straight	3.3	0.23	53.81		1
B	4	130 m	2.36	0.26	54.45	0.02	1
B	4	250 m	2.72	0.25	54.18	0.01	0.76
B	4	340 m	2.95	0.22	51.49	0.01	0.89
B	4	Straight	3.47	0.26	53.22		0.88
B	Control	130 m	2.52	0.26	59.86	0.04	0.89
B	Control	250 m	2.97	0.22	61	0.01	0.8
B	Control	340 m	3.22	0.21	60.2	0.01	0.79
B	Control	Straight	3.67	0.25	57.86		0.8
.	Baseline	130 m	2.83	0.2	55.04		1.05
.	Baseline	250 m	3.81	0.16	50.9		0.68
.	Baseline	340 m	4.34	0.14	51.71		0.73
.	Baseline	Straight	4.44	0.18	53.27		0.68
M	1	130 m	2.52	0.28	54.02	0.02	1.11
M	1	250 m	2.87	0.25	52.31	0.02	0.98
M	1	340 m	2.97	0.23	51.34	0.02	0.96
M	1	Straight	3.5	0.27	53.68	0.01	0.79
M	2	130 m	2.39	0.28	54.18	0.04	1.01
M	2	250 m	2.77	0.24	55.42	0.01	1.1
M	2	340 m	2.85	0.26	54.91	0.01	0.96
M	2	Straight	3.35	0.28	54.72	0.01	0.97
M	3	130 m	2.43	0.26	53.28	0.02	0.99
M	3	250 m	2.85	0.24	53.91	0.02	1.03
M	3	340 m	2.96	0.24	54.55	0.02	1.27
M	3	Straight	3.61	0.26	51.76	0.02	1.17
M	4	130 m	2.41	0.29	53.43	0.03	0.97
M	4	250 m	2.51	0.3	53.03	0.03	0.89
M	4	340 m	2.9	0.24	52.8	0.02	1.16
M	4	Straight	3.44	0.26	50.93	0.02	0.92

M	Control	130 m	2.52	0.25	53.1	0.02	0.94
M	Control	250 m	3.16	0.24	51.76	0.01	0.98
M	Control	340 m	3.26	0.21	50.77		0.98
M	Control	Straight	3.86	0.24	51.14	0.01	0.81
.	Baseline	130 m	2.64	0.23	55.04	0.01	0.86
.	Baseline	250 m	3.25	0.2	52.25		0.8
.	Baseline	340 m	3.89	0.18	50.61		0.77
.	Baseline	Straight	4.41	0.18	51.67		0.97
P	1	130 m	2.46	0.25	56.95	0.01	0.98
P	1	250 m	3.06	0.23	58.81	0.01	0.87
P	1	340 m	3.22	0.22	58.59	0.01	0.84
P	1	Straight	3.9	0.21	58.1		0.94
P	2	130 m	2.36	0.26	60.9	0.02	0.82
P	2	250 m	3.09	0.23	57.52	0.03	0.83
P	2	340 m	2.98	0.25	56.68	0.04	0.8
P	2	Straight	3.42	0.28	57.23	0.01	0.68
P	3	130 m	2.59	0.26	61.76	0.01	0.93
P	3	250 m	3.06	0.24	60.83	0.02	0.87
P	3	340 m	3.07	0.23	58.48	0.01	0.83
P	3	Straight	3.73	0.26	60.06	0.01	1.06
P	4	130 m	2.52	0.26	64.69	0.03	0.84
P	4	250 m	3.08	0.25	63.24	0.03	0.89
P	4	340 m	3.15	0.24	61.4	0.03	0.85
P	4	Straight	3.46	0.22	63.99	0.01	0.82
P	Control	130 m	2.56	0.26	62.71	0.02	1.01
P	Control	250 m	3.17	0.22	61.86	0.01	0.92
P	Control	340 m	3.31	0.21	61.29	0.01	1
P	Control	Straight	3.75	0.2	59.45		0.9
.	Baseline	130 m	2.8	0.21	56.33	0.01	0.79
.	Baseline	250 m	3.43	0.17	54.66		0.75
.	Baseline	340 m	3.9	0.18	52.75		0.76
.	Baseline	Straight	4.33	0.21	54.38		0.62
GROUP	TRT	CRV	TLC	SDLP	HDWY	EXC	SDVEL

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
			42.01	1.14	0.35	-0.56

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
		130 m	31.18	1.02	0.27	-0.61
		250 m	41.67	1.11	0.37	-0.54
		340 m	45.4	1.18	0.39	-0.52
		Straight	55.37	1.32	0.43	-0.58

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
	1		41.89	1.08	0.38	-0.44
	2		42.9	1.12	0.36	-0.56
	3		44.07	1.17	0.36	-0.6
	4		43.92	1.16	0.36	-0.63
	Control		37.37	1.16	0.31	-0.62

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
	1	130 m	31.69	0.98	0.29	-0.5
	1	250 m	41.72	1.04	0.39	-0.42
	1	340 m	45.82	1.14	0.41	-0.41
	1	Straight	52.75	1.22	0.44	-0.41
	2	130 m	31.86	1.02	0.28	-0.62
	2	250 m	42.7	1.11	0.37	-0.54
	2	340 m	46.06	1.15	0.4	-0.52
	2	Straight	56.47	1.26	0.45	-0.55
	3	130 m	32.35	1.1	0.27	-0.67
	3	250 m	44.33	1.12	0.38	-0.58
	3	340 m	47.26	1.2	0.39	-0.54
	3	Straight	57.98	1.34	0.44	-0.62
	4	130 m	32.62	1.03	0.28	-0.64
	4	250 m	43.47	1.16	0.36	-0.62
	4	340 m	47.69	1.18	0.4	-0.6
	4	Straight	57.73	1.36	0.43	-0.71
	Control	130 m	27.47	0.97	0.26	-0.64
	Control	250 m	36.31	1.12	0.32	-0.66
	Control	340 m	40.23	1.22	0.33	-0.52
	Control	Straight	51.92	1.43	0.37	-0.66

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
B			48.98	1.17	0.39	-0.43
M			39.89	1.12	0.35	-0.58
P			37.56	1.13	0.32	-0.66

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
B		130 m	40.94	1.04	0.32	-0.48
B		250 m	48.67	1.15	0.39	-0.41
B		340 m	50.22	1.2	0.41	-0.39
B		Straight	60.15	1.33	0.46	-0.46
M		130 m	29.47	1	0.29	-0.67
M		250 m	39.98	1.12	0.36	-0.56
M		340 m	43.23	1.16	0.37	-0.54
M		Straight	53.91	1.31	0.42	-0.57
P		130 m	24.14	1.03	0.21	-0.68
P		250 m	36.85	1.07	0.35	-0.65
P		340 m	42.85	1.17	0.38	-0.62
P		Straight	52.05	1.32	0.41	-0.71

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
B	1		49.3	1.09	0.41	-0.36
B	2		47.45	1.06	0.4	-0.42
B	3		50.77	1.15	0.4	-0.46
B	4		48.52	1.13	0.38	-0.48
B	Control		48.88	1.39	0.34	.
M	1		42.22	1.13	0.37	-0.54
M	2		41.88	1.16	0.35	-0.6
M	3		41.01	1.16	0.35	-0.6
M	4		43.42	1.16	0.38	-0.59
M	Control		30.93	1.01	0.31	.
P	1		34.68	1.02	0.34	-0.39
P	2		39.62	1.13	0.34	-0.64
P	3		40.95	1.2	0.33	-0.73
P	4		40.18	1.2	0.32	-0.84
P	Control		32.42	1.08	0.29	-0.62

GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT
B	1	130 m	45.71	1	0.34	-0.37
B	1	250 m	47.63	1.04	0.42	-0.34
B	1	340 m	48.76	1.14	0.43	-0.35
B	1	Straight	58.94	1.2	0.49	-0.38
B	2	130 m	39.32	0.98	0.33	-0.5
B	2	250 m	48.2	1.06	0.4	-0.41
B	2	340 m	47.63	1.09	0.43	-0.36
B	2	Straight	58.76	1.14	0.51	-0.41
B	3	130 m	42.22	1.03	0.33	-0.51
B	3	250 m	52.94	1.15	0.41	-0.44
B	3	340 m	50.79	1.18	0.41	-0.43
B	3	Straight	60.54	1.27	0.47	-0.49
B	4	130 m	40.96	1.07	0.31	-0.52
B	4	250 m	48.48	1.1	0.39	-0.48
B	4	340 m	50.47	1.13	0.42	-0.42
B	4	Straight	56.98	1.27	0.45	-0.56
B	Control	130 m	37.24	1.1	0.31	.
B	Control	250 m	46.41	1.35	0.34	.
B	Control	340 m	53.5	1.48	0.37	.
B	Control	Straight	65.54	1.78	0.39	.
M	1	130 m	30.42	1.02	0.3	-0.64
M	1	250 m	42.53	1.1	0.39	-0.51
M	1	340 m	47.3	1.21	0.4	-0.51
M	1	Straight	55.08	1.29	0.43	-0.48
M	2	130 m	32.65	1.03	0.31	-0.68
M	2	250 m	41.55	1.18	0.35	-0.57
M	2	340 m	44.84	1.19	0.37	-0.55
M	2	Straight	55.09	1.34	0.42	-0.58
M	3	130 m	28.75	1.07	0.27	-0.69
M	3	250 m	40.89	1.12	0.36	-0.56
M	3	340 m	45.64	1.22	0.37	-0.55
M	3	Straight	56.47	1.34	0.43	-0.63
M	4	130 m	33.97	1.02	0.33	-0.65
M	4	250 m	42.79	1.19	0.37	-0.59
M	4	340 m	45.84	1.16	0.4	-0.55
M	4	Straight	58.76	1.36	0.44	-0.58
M	Control	130 m	21.53	0.87	0.24	.
M	Control	250 m	32.15	1	0.33	.
M	Control	340 m	32.5	1.04	0.32	.
M	Control	Straight	44.16	1.23	0.36	.

P	1	130 m	21.95	0.92	0.22	-0.43
P	1	250 m	35.29	0.98	0.36	-0.41
P	1	340 m	41.4	1.09	0.41	-0.36
P	1	Straight	44.22	1.18	0.41	-0.37
P	2	130 m	23.9	1.04	0.2	-0.67
P	2	250 m	38.91	1.08	0.37	-0.64
P	2	340 m	45.71	1.17	0.4	-0.62
P	2	Straight	55.58	1.3	0.44	-0.66
P	3	130 m	27.28	1.21	0.21	-0.82
P	3	250 m	40.03	1.1	0.36	-0.72
P	3	340 m	45.52	1.2	0.38	-0.66
P	3	Straight	56.93	1.41	0.41	-0.75
P	4	130 m	23.71	1.02	0.2	-0.81
P	4	250 m	39.63	1.18	0.33	-0.8
P	4	340 m	46.91	1.25	0.38	-0.83
P	4	Straight	57.44	1.44	0.41	-0.99
P	Control	130 m	24.11	0.96	0.22	-0.64
P	Control	250 m	30.39	1	0.3	-0.66
P	Control	340 m	34.7	1.14	0.31	-0.52
P	Control	Straight	46.08	1.28	0.36	-0.66
GROUP	TRT	CRV	VR	DWELL	LFREQ	NEGRT